AN INTEGRATED STOCHASTIC MULTI-OBJECTIVE DOWNSTREAM OIL & GAS SUPPLY CHAIN MODEL FOR TACTICAL DECISION MAKING

BY

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To my
Beloved Mother, Father, Brothers & Sisters, Wife, Sons, and Daughter, I dedicate this work

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LIST OF ABBREVIATIONS

HCSC	:	Hydrocarbon Supply Chain
$	:	Dollar
MBL	:	Million Barrel
M	:	Million
BL	:	Barrel
LP	:	Linear Programming
MOD	:	Multi-objective Deterministic
MOS	:	Multi-objective Stochastic
MOR	:	Multi-objective Risk
MSCF	:	Million Standard Cubic Feet
GOSPs	:	Gas Oil Separation Plants
VaR	:	Value at Risk
CVaR	:	Conditional Value at Risk
NGL	:	Natural Gas Liquid
OPEC	:	Organization of the Petroleum Exporting Countries

ABSTRACT

Full Name : [Ahmed Mansoor Hussein Ghaithan]

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The aim of the dissertation is to develop three multi-echelon, multi-item, multi-period and multi-objective mathematical models for tactical planning of an integrated downstream oil and natural gas supply chain.

The dissertation begins with a comprehensive review of the literature on mathematical modeling of Hydrocarbon Supply Chain (HCSC). The previous works are classified based on the modeling approach into deterministic and stochastic models. Under each approach, the papers are classified based on strategic and tactical planning horizon models and integration of HCSC based on type of considered network.

The second part of the dissertation models the downstream segment of oil and gas supply chain under the assumption of fixed and known parameters. Three conflicting objectives are optimized; total cost, total revenue, and service level. The goal is to determine tactical processing, distribution and marketing plans simultaneously. The formulated model is an integrated Multi-Objective Deterministic (MOD) model.

The third part of the dissertation extends the MOD model to study the effect of uncertainty in market conditions. The proposed and obtained model is Multi-Objective Stochastic (MOS) model. Uncertainties incorporated to the proposed model from variations of

demands and prices of petroleum products. The MOS model is formulated based on the two-stage approach. The uncertain parameters are represented by discrete realizations with specific probability of occurrence.

The risk associated with uncertain parameters in the stochastic model is quantified and studied through employing CVaR risk measure of total cost and total revenue in the fourth part of the dissertation. The resulted model is Multi-Objective Risk (MOR) model. The purpose of the MOR model is to avoid developing a tactical plan with high total cost and low revenue.

The applicability and utility of the three proposed models are validated and evaluated using the case of Kingdom of Saudi Arabia HCSC. The three models were solved using improved augmented ε-constraint algorithm to generate Pareto optimal solutions. A valuable and practical sensitivity analysis was conducted to study the effect of key controlled and uncontrolled parameters on the obtained results and some managerial insights were derived.

ملخص الرسالة

الاسم الكامل: أحمد منصور حسين غيثان

عنوان الرسالة: نموذج متكامل عشوائى متعدد الاهداف للمرحله السفلى من سلاسل امداد النفط و الغاز لصنع القرار التكتيكى.

التخصص: الهندسة الصناعية و النظم

تاريخ الدرجة العلمية: مايو 2017م

تهدف هذة الأطروحة الى تطوير ثلاثة نماذج رياضية متعددة المراحل، متعددة المنتجات، متعددة الفترات و متعددة الأهداف للمرحلة السفلى من سلاسل امداد النفط و الغازات وذلك لايجاد امثل الحلول التكتيكية و دراسة المفاضلات الناتجة من تعدد الدوال الهدفية.

يعرض الجزء الأول من الأطروحة مراجعة للمنشور في مجال نمذجة سلاسل الامداد الهيدروكربونية و تم تقييم الابحاث المنشور و تصنيفها حسب طبيعة صنع القرار (تكتيكي، استراتيجي) و حسب نوع النموذج اذا كانت برمترات النموذج ثابتة او عشوائية. و خلصت مراجعة المنشور ان هناك فجوة لعدم استخدام نماذج ذات دوال هدفية متعددو لدراسة سلاسل الامداد للمواد الهيدروليكية.

و طور الجزء الثاني من الاطروحة نموذج متعدد الدوال الهدفية. و شملت الدوال تخفيض التكلفة الكلية و تعظيم كل من الايرادات الكلية و مستولى الخدمة. و تم دراسةعمليات اتخاذ القرار في الانتاج والتوزيع و عرضت عدة نقاط توضح المفاضلة بين الحلول التي تكون أمثل حسب منظور بريتو (Pareto). و الجدير ان هذا النموذج يفترض ان برميترات النموذج ثابتة فهو يتغاضى عن العشوائية التي هي من طبيعة بعض البرميترات مثل السعر و الطلب.

طورالجزء الثالث من الاطروحة نموذج عشوائي متعدد الدوال الهدفية لدراسة تاثير العشوائية في بعض البرميترات مثل السعر و الطلب على المنتجات البترولية. تم تطوير النموذج باستخدام نموذج اتخاذ القرار على مرحلتين (two-stage stochastic) مع افتراض العديد من السيناريوهات للبرميترات العشوائية.

في الجزء الرابع من الاطروحة تم تعديل النموذج العشوائى ليصبح نموذج إدارة المخاطر المالية باستخدام CVaR كمقياس للخطر في دوال التكلفة والايرادات الكلية. الغرض من نموذج المخاطر هو تجنب وضع خطة تكتيكية يترتب عنها إجمالي تكاليف عالية و دخلا منخفض.

وتم تقديم دراسة لحالة سلسلة الامداد للنفط والغاز السعودية لأثبات عملية النماذج. تمت عملية حل النماذج الثلاثة باستخدام الطريقة المطورة من (ε-constraint). و تم إجراء تحليل الحساسية لدراسة بعض البرميترات المتغيرة والعشوائية لاستخلاص بعض الأفكار الإدارية.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Petroleum industries, including oil and gas companies, play an important role in the world economy because they supply the necessary products to sustain the world energy supply. The supply chain of oil and gas is known as HCSC. Where, oil supply network comprises oil fields, oil and gas separation plants (GOSPs), primary storage facilities, oil processing plants, refinery plants, secondary storage facilities, and demand nodes. While natural gas supply chain involves gas fields, storages facilities, gas plants, fractionation plants, secondary storages facilities, and demand nodes.

The oil and gas networks overlaps in many entities and shares some of products. For example, the GOSPs and markets are available in both networks. Regarding to shared products, the input to gas plants are associated gas from GOSPs and non-associated gas from gas fields. Also, the output from refinery plant involves liquid petroleum gas (LPG); propane or butane which are the same outputs from fractionation plant. Therefore, for countries that have oil and gas reserves, it is important to integrate and optimize both oil and gas networks as a single integrated supply chain. The oil and gas supply chain is a multi-echelon, multi-dimension, and multi-period. Such a complex system leads us to multi-objective optimization problem. The purpose of the dissertation is to develop a class of multi-objective deterministic and stochastic models for tactical planning of HCSC with considering risk.

The rest of this chapter is organized as follows: section 1.2 provides overview of HCSC followed by decision making in HCSC in section 1.3. Section 1.4 highlights the dissertation motivation followed by concept of multi-objective optimization in section 1.5. Section 1.6 outlines the objectives of the dissertation. The chapter is closed by the dissertation organization.

1.2 Overview of Hydrocarbon Supply Chain (HCSC)

1.2.1 Network Description

The HCSC is classified into two parts: upstream and downstream segments. The upstream of HCSC consists of various entities, namely, oil and natural gas reservoirs, oil and natural gas wells, GOSPs, gas plants, storage facilities, and primary transportation routes. The upstream segment is responsible for the following activities: explorations of sour oil and natural gas, development of oil and natural gas fields which involve drilling, production, separation, storage, and transportation of oil and gas.

The downstream segment of HCSC consists of the following ties: oil processing plants, gas plants, refinery plants, fractionation plants, bulk plants, demand nodes (international, industries, and domestic), and import nodes. The downstream segment is illustrated in Fig.1.1. Many activities occurred along the downstream segment of HCSC including: crude oil and natural gas transportation, crude oil processing, natural gas separation, crude oil refining, refined products transportation, storage, distribution, and marketing. The products produced from oil fields are called well head streams (sour oil). The main well head stream types are Arabian Extra Light, Arabian Light, Arabian medium, and Arabian Heavy. Each oil field can produce a special type of well head stream. Two types of natural gas; associated gas and non-associated gas are extracted from oil fields and gas fields, respectively.

The final petroleum product goes along of many processing and transforming activities to be ready for final use; as follows: Well head stream (sour oil) is streamed to oil processing plants for sweetening by removing of sulfur. After sweetening, the well head stream is now called crude oil. The crude oil of different types is transported through routes to terminals to satisfy international demands. Some of it is used as raw material for local refinery plants. In a refinery plant, the crude oil is transformed through multi-operations to oil refined products based on their compositions. The main oil refined products are LPG, Naphtha, Gasoline, Diesel, Kerosene, Fuel oil, and Asphalt.

Then oil refined products are transported to storage bulk plants through specific transportation mode to be ready for distribution into different domestic regions and industries. Some of oil refined products are exported through terminals to satisfy the international markets demand. While, the shortage in meeting local and industry demands is imported from international markets.

On the other path, the natural gas either associated from ($GOSP_S$) or non-associated from (gas fields) is transferred to gas plant for separation into heavy gas streams; Natural Gas Liquid (NGL), methane, and hydrogen sulfide. The NGL goes to fractionation plant for further processing and separation into its components; gas products (ethane, propane, butane and natural gasoline). The methane from gas plant and ethane from fractionation plant are used as raw material by industry. Other gas products from fractionation plant are consumed locally. In case of excess gas products, they exported and shortages for local demand are imported through terminal.

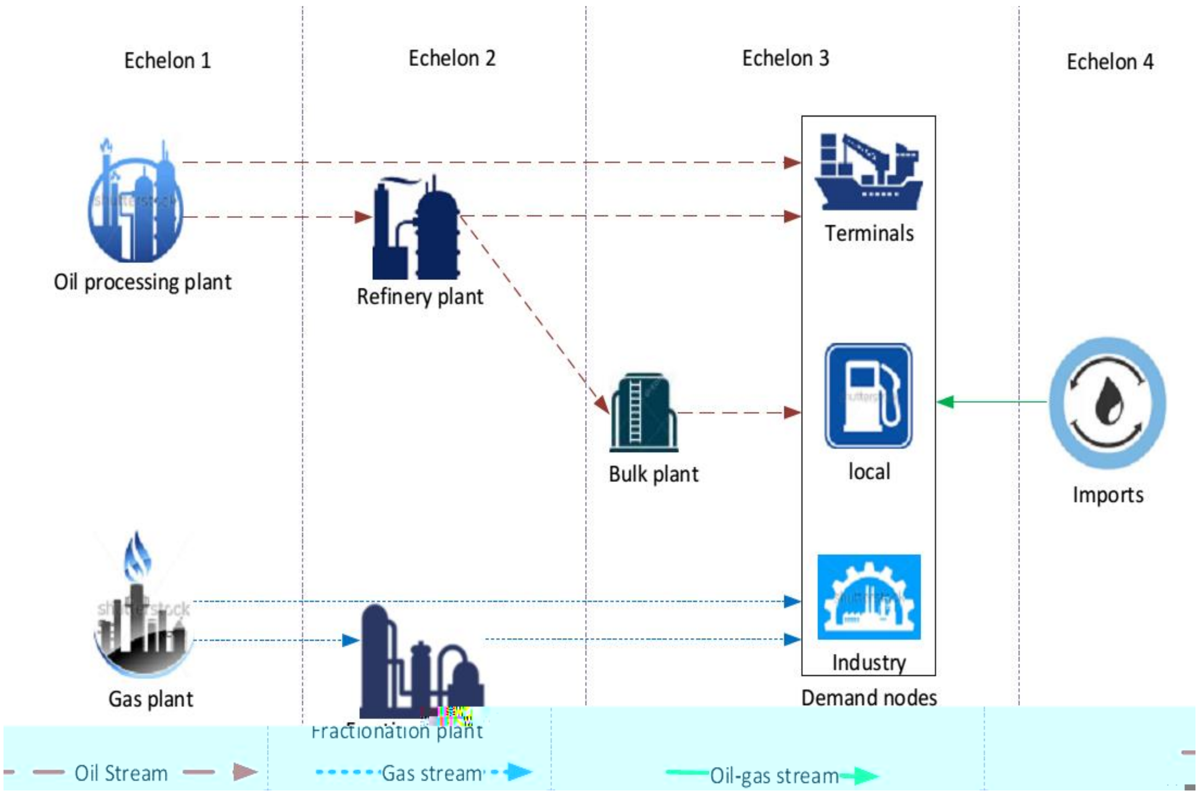


Figure 1.1 Schematic representation of downstream HCSC

For more information about each node in the HCSC network they are defined briefly below:

a) Oil Processing Plant

The oil processing plant consists of multiple spheroids and stabilizer columns. The sour oil from (GOSPs) is the input to oil processing plant. In the oil processing plant, sour oil is processed into sweet crude oil by removing sulfur. The sulfur can be processed more and commercialized in markets as a fertilizer. The sweet crude oil is then transported to international markets and local refinery plants for transforming it into its oil refined products.

b) Gas Plant

The gas plant is a complex gas processing unit that receives sour natural gas; associated and/or non-associated gas from GOSPs and/or gas fields, respectively. Two functions occur at gas plant, first the sour natural gas is cleaned by removing impurities and hydrogen sulfide. After removing the hydrogen sulfide, the natural gas is called sweet natural gas. Second, the sweet natural gas is further separated through compression and chilling into NGL and methane. The methane (in gaseous state) is then transported to petrochemical industry to be used as feedstock and/or fuel. The NGL (in liquid state) is commercialized as it is or it needs more fractionation into its gas products in a separate facility called fractionation plant.

c) Fractionation Plant

The fractionation plant receives NGL from gas plants and fractionates it more into gas products in (gaseous state). The gas products (ethane, propane, butane, and natural gasoline) are then ready to be used for international, industry, domestic consumptions.

d) Refinery Plant

The refinery plant receives sweet crude oil from oil processing plant and transforms it through multi-operations to oil refined products based on their compositions in the input stream. Based on refinery plant configuration, specifications, and utilized technology, a specific type of crude oil and produce different types and quantities of refined products. In general, the oil refined products are LPG, Naphtha, Gasoline, Diesel, Kerosene, Fuel oil, and Asphalt. The refined oil refined products are transported to storage bulk plants through specific transportation mode to be ready for distribution into different regions, industrial cities, and some are exported through terminals to the international markets.

e) Bulk Plant

The bulk plant is a storage facility for refined oil products. A bulk plant typically has many big tanks for storing each oil refined products product separately. The bulk plants are built close to the final customers. From bulk plant, the oil refined products are distributed to its demand node.

f) Terminals

Terminals are facilities for the storage of crude oil, oil and gas products and from which these products are usually transported to end users or further storage facilities. The terminal has tanks, either above ground or underground, and framework for unloading of products into tankers or marine. Typically, the terminals are constructed in the sea.

g) Domestic

Domestic represents the end user of petroleum products. It involves gas stations, airports, hospitals, etc.

h) Industries

The industries comprise petrochemical plants, water desalination plants, and power generation plants. The petrochemical plants utilized gas products as feedstock or as fuel. The petrochemicals are classified based on type of feed gas into: methane-based, ethane-based, and butane-based petrochemical plants. Petrochemical products are Ethylene

Caustic, Soda Styrene, Ethanol, Ethylene dichloride, LLPDE, HDPE, Urea, Sulfuric Acid, Melamine, Methanol, etc.

In water desalination plant, salts and minerals are removed from water to be pure for human needs. The water desalination plants are operated using methane, ethane, and/or oil products. Also, the power generation plant uses methane, ethane, and/or oil refined products as fuel.

i) Imports

Imports represent the international markets of crude oil, oil and gas products. Each petroleum producing country has its own market at which consumers come to buy the needed products. Almost, the prices at all imports in the world are the same and it is specified by OPEC organization.

1.2.2 Problem Statement

As stated above, the oil and gas networks overlap in many entities and share some products. Therefore, the two networks must be optimized in a single supply chain. Accordingly, a tactical planning models will be presented given petroleum demands, entities and route capacities, market price in each period, production, holding and transportation costs in each time period. The tactical decisions related to the above stated network include decisions such as determining optimal processing plans, flow volume between nodes import and export volumes, and allocation of local customer to bulk plants.

The HCSC comprises uncertain and uncontrolled parameters such as demand, price, supply, yields, etc. For example, in the last two years, huge variations in the energy demand

and price was noted. Therefore, during modeling the HCSC it is important to take into account these uncertainties within a multi-dimensional framework and in a way of not losing market share and satisfying gas products demand of industry plants. The trade-offs between satisfying economic goals and keeping sustain in market must be studied. The objectives are to minimize the total cost, maximize the total revenue, and maximize service level. The two-stage stochastic programming approach is employed to model the problem involving uncertainties.

The uncertain parameters are represented by a finite number of realizations or scenarios. Therefore, the two-stage stochastic programming approach contains uncertain parameters in its objective function and/or constraints. As a result, the optimization process must optimize a model that contains distribution function of these parameters (e.g., the expected value). The essential disadvantage of this process is the ignoring other parameters depicting the distribution. In order to tackle the risk associated with this ignorance, a term measuring the risk must be added to either the objective function and/or the constraints. The purpose of risk model is to avoid the risk of exceeding a certain limit of costs and/or the risk of not exceeding a desired levels of revenue.

1.3 Decision Making of HCSC

Optimizing of HCSC is a complicated task since HCSC is a long supply chain that involves many integrated entities and complex activities. In general, optimization of HCSC is the activity of making decisions regarding specific variables while satisfying suitable goals or objective functions and subjected to limitations. In general, decision making process is divided based on the planning horizon into three levels; strategic, tactical and operational levels. The strategic decisions are made for long term range from 2 years up to 5 years. The tactical decisions are decided for mid-term and range from 1 months up to 12 months. The operational decisions are short-term decisions and range from days to months. The tactical decisions in HCSC involve production, processing, distribution quantities, flow of products between each two nodes of the HCSC, importation, and exportation volumes.

Based on the type of information, decision making process are classified into three environments: certainty, uncertainty, and risk environment. In the certainty environment, deterministic optimization modeling is utilized to achieve the optimal solutions. In the uncertainty environments (those in which one cannot assess the probability of output of decisions), a robust programming approach is applied. In risk situations (those in which one is able to assess the probability of uncertain parameters), a stochastic programming approach is utilized to model such situations.

1.4 Dissertation Motivation

Petroleum companies play an important role in the world economy due to the fact they supply a major part of the global energy needs. HCSC is considered one of the most complicated networks since it comprises many interconnected entities. Integrating and optimizing oil and natural gas industries in a single supply chain is important for countries that have oil and gas reserves. Also, considering and modeling all entities in the oil and natural gas supply chain is vital to the petroleum producing countries to ensure their prosperity.

Efficient management of integrated oil and natural gas supply chain leads to high income. Moreover, energy market is unstable since variation in the market conditions is a problem that need to be considered during modeling and optimization. For example, in the period 2014-2016, petroleum product prices have been reduced sharply, as a result, petroleum countries faced budget deficit, and then, some of projects are stopped. Therefore, petroleum producing countries have planned to reduce their oil production to overcome this impairment. However, if they reduce oil production, they may lose market share and could not satisfy gas products demand of industrial plants from non-associated gas. Therefore, petroleum countries have to change their production and marketing plans strategically and tactically within a multi-dimensional framework. These plans must be based on satisfying multiple objectives. The trade-offs between economic goals, keep sustain in market, and financial risk must be considered.

1.5 Multi-Objective Optimization

Optimization problems with single objective function can be solved easily using the well-known methods to get one solution called optimal solution. Oppositely, in optimization with more than one objective function, more than one optimal solution, called Pareto optimal points (efficient, non-dominated, non-inferior) are generated. The efficient solutions are the solutions that cannot be improved in one objective function without deteriorating their performance in at least one of the rest objectives, (Mavrotas, 2009). After getting the Pareto set of optimal points, it is the role of the decision maker to choose the ‘‘most preferred” solution from the set of Pareto points. The shape of Pareto-optimal represents the trade-off among the considered objectives.

The solution methods of multi-objective problems are classified based on the stage where the decision maker is involved to set his/her preferences into three categories , (Hwang and Masud, 2012): priori, interactive, and posteriori methods. In a priori methods, the decision maker is involved before solving the problem. While in the interactive methods, phases of dialogue with the decision maker are interchanged with phases of calculation and the process usually converges after few iterations, to the most preferred solution. The main drawback of the first and second category is that the decision maker does not have a whole image about the trade-off before getting the Pareto set.

To avoid the above mentioned drawbacks, the posteriori methods, such as ε-constraint method, first generate the set of Pareto optimal points, then the decision maker is asked to choose among these sets. In the usual ε-constraint method the objective function with the highest priority is optimized by adding the other objectives as unbinding constraints. The set of Pareto optimal points including weakly efficient solutions are then generated. To remove weakly efficient solutions, Mavrotas and Florios (2013) developed a new version of ε-constraint method called improved augmented ε-constrained (see Appendix B) to generate Pareto optimal sets without weakly efficient solutions by optimizing the objective of highest priority while the other objectives are added to the feasible region as binding constraints. The Improved Augmented ε-Constraint method offers more flexibility to solve the multi-objective problem compared to the other methods. In the improved augmented ε-Constraint method, the density of the Pareto optimal solutions is controllable and the decision maker can select "most preferred" solution among them by utilizing a multi-criteria decision making approach.

1.6 Dissertation Objectives

The objective of the dissertation is to develop three multi-periods, multi-item, and multi-objective mathematical models for integrated downstream oil and gas supply chain for tactical decision making. The three models are: multi-objective deterministic model, multi-objective stochastic model, and multi-objective risk model. The three models are used to address the following issues:

1. Assess trade-offs among three conflicting objectives related to downstream HCSC; minimize total cost, maximize total revenue, and maximize service level.
2. Study the impact of variations in market conditions on the tactical decisions of HCSC through extending the deterministic model to a stochastic model based on two stage stochastic programming approach.
3. The risk associated with uncertainty in market conditions is quantified and measured by CVaR and used to develop a multi-objective risk model.
4. Apply of the three proposed models to validate and evaluate their applicability using a real case of Kingdom of Saudi Arabia HCSC. The models are solved using the improved augmented ε-constraint algorithm to generate Pareto optimal solutions. The models results are compared and several managerial insights are derived.

1.7 Organization of the Dissertation

The rest of this dissertation is organized as follows: **Chapter 2** provides a literature review focusing on two categories; deterministic models and stochastic models. Under each category, the models are classified and reviewed based on planning horizon and type of network. The review identifies some of the gaps that need to be addressed in future research.

Chapter 3 formulates the multi-objective deterministic model and tests it on a real case from Kingdom of Saudi Arabia HCSC. The results of the model and sensitivity analysis is also presented in the chapter. **Chapter 4** develops a two stage stochastic programming model by modifying the multi-objective deterministic model. The results from the deterministic and stochastic models are discussed. A sensitivity analysis is conducted by considering two real market situations when: price high – demand low and price low – demand high.

Chapter 5 highlights the concept of risk and modifies the multi-objective stochastic model by formulating multi-objective risk model considering risk. The results from the three models are compared. Sensitivity analyses based on different risk levels and risk confidence levels are conducted. **Chapter 6** summarizes the whole work, highlights dissertation contribution, and outlines directions for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In recent years, several studies have been conducted on the optimization of HCSC. This chapter presents the relevant literature to the dissertation work. The literature review consists of mathematical programming models developed for HCSC. Section 2.2 presents deterministic models for strategic and tactical planning horizons. Section 2.3 reviews strategic and tactical models under uncertain environment. Section 2.4 contains multi-objective models for HCSC. These models are classified and research gaps are outlined. Finally, section 2.5 concludes this chapter.

2.2 Deterministic Models

The supply chain is a network of integrated facilities that interact with each other to add value to the final customer. The HCSC is divided into two major segments: upstream and downstream segments. The HCSC can be classified based on the type of product considered into oil supply chain, gas supply chain, and oil and gas supply chain. In this section, the research papers that discuss downstream oil-oriented, gas-oriented, and oi-gas oriented HCSC in the context of certain environments will be reviewed.

Regarding oil supply chain models, (Sear, 1993) developed a strategic logistic planning model for main oil refined products supply chain. He considered refineries, storage depot, imports and transportation modes. Sear explained the types of bulk transportation used, the main product classes, and addressed the risks associated with changes to the logistics infrastructure. The models did not consider processing of crude oil. Whereas, (Persson and Göthe-Lundgren, 2005) increased the complexity of the problem by considering refinery scheduling optimization problem. The model planned shipping process between refineries and depots, in addition tanker routes and delivery quantities to depots are considered. The model did not consider the shipping activities with customers (i.e. assignment of customers to depots).

(Al-Qahtani and Elkamel, 2008a) formulated a mixed integer linear programing (MILP) model for planning of the refining industry as an integrated network of multi-site facilities. They considered crude oil processing at refineries and marketing of refined oil refined products locally and internationally, and imports of refined oil products. The importation and exportation of crude oil were not considered in the model. The model used for decisions related to capacity expansion and network integration alternatives to minimize the total costs under known and fixed costs and demands. Next, (Al-Qahtani and Elkamel, 2008b) extended (Al-Qahtani and Elkamel, 2008a) work by integrating of multisite refinery and petrochemical entities. They tackled the same problem with extra decision options such as facility relocation.

(Elkamel et al., 2008) investigated the integration of refinery planning and the environmental impact of CO2 under different levels. The aim of the research was to maintain product quality specifications while lowering CO2 emission levels simultaneously. The model did not consider imports and exports for oil refined products and crude oil. (Kim et al., 2008) formulated a mixed integer non-linear programing

(MINLP) model to optimize production planning of multi-site refineries and distribution planning to markets for profit maximization. They considered oil supply chain comprises, refineries distribution centers, and markets. Three strategies for refinery supply were considered: supply network for individual refineries, collaborative supply network of all refineries, and integrated network of all the refineries. The model did not consider the imports. The sensitivity of the proposed models need to be examined against the variation in both demand and price.

(Al-Qahtani and Elkamel, 2009) formulated a MILP model to coordinate the operation of multi-refinery plants. The objective is to minimize annual operating and capital costs based on decisions regarding to capacity expansion, production levels, and blending levels. (Kuo and Chang, 2008a) proposed a MILP model for planning and scheduling of the refineries to maximize total profit of the petroleum supply chain. Later, (Kuo and Chang, 2008b) extended the (Kuo and Chang, 2008a) work by coordinating the planning and scheduling decisions of the refinery and petrochemical plants to maximize total profit of the petroleum supply chain. Both models ignored the non-linearity in blending operations. (Guyonnet et al., 2008) formulated two models: both integrated and non-integrated models for crude oil unloading operations, production planning, and distribution processes. They found out that the integrated model results in higher profit due to lower lost demand, safety stock, and unsatisfied demand.

(Fernandes et al., 2011) formulated a MILP model for long-term planning decisions of the downstream activities. Depot locations, capacity planning, and quantities transported from refineries to depots and from depots to customers are identified. The model boundary was limited to domestic distribution, that is, the international demand was not considered.

Accordingly, the downstream activities were not complete. (Fernandes et al., 2013) considered the effect of globalization (e.g., imported supplies and exported products). (Fernandes et al., 2014) extended the work of (Fernandes et al., 2013) by adding collaborative design, operator-profit incorporation, standardized resources, multistage and dynamic inventories, and piecewise price linearization. The current model includes also transportation generalization and uses transport-mode families and product families associated with resources. The families may contain one or many transport modes or products. (Fiorencio et al., 2015) developed a MILP for strategic decision related to: depot locations, capacities (e.g., refinery, depot, retailer), transportation modes and transportation routes.

(Kazemi and Szmerekovsky, 2015) built a MILP model considering multi-echelon, multi-product and multi-transportation mode strategic model for downstream oil supply chain to minimizes total cost. The model integrates refineries, distribution centers, transportation modes and demand nodes. The model determines distribution center locations, capacities, transportation modes, and transfer volumes. The model considered local refining of gasoline, diesel, and jet fuel in addition to imports. (J. l Jiao et al., 2010) proposed a MILP model for Chinese petroleum supply chain. The model integrates crude oil supply, refinery, petrochemicals and downstream chemicals markets. The model considered imported and local crude oil, refined oil products, associated gas, petrochemical products. They assumed unlimited capacity of entities and routes, and shortage was allowed. (Chen et al., 2010) proposed a simple model, a few number of logistic centers, to minimize the cost of imported crude oil. Cost elements includes the transportation costs, operation cost in logistics centers, handling costs and domestic transportation cost.

Regarding gas-supply chain models, (Hamedi et al., 2009) presented a case study considering the transmission and distribution planning of natural gas. A MINLP model has been developed to minimize costs of transportation and processing. The model contains a constraint to linearize the objective function.

Regarding oil and gas supply chain models, (Duffuaa et al., 1992) developed a linear programming model for the crude oil and associated gas supply chain in the Kingdom of Saudi Arabia. The model addressed the effect of crude oil production on satisfying the industries demand of methane and ethane from the associated gas. The model considered a ceiling of 4.5 million barrels per day (MBL/day) as an Organization of the Petroleum Exporting Countries (OPEC) quota. The involved entities in the proposed supply chain are oil fields, oil and gas separation plants, gas plants, fractionation plants, and petrochemicals that utilized gas products as feedstock or fuel. The proposed model is deterministic in nature and did not address uncertainty. The proposed model did not consider transforming of crude oil at refinery plants, storing of oil at bulk plants, and distribution of oil-products into local and/or international markets. Table 2.1 summarizes the deterministic models in terms of type of supply chain, modeling approaches, performance measures, and decision levels.

Table 2.1 Summary of the selected deterministic papers.

Reference	Network		Modelling Approaches				Performance measure			Decision levels	
	Oil	Gas	LP	MLP	NLP	MNLP	CM	PM	Other	Strategic	Tactical
(Duffuaa et al., 1992)	√	√	√				√				√
(Sear, 1993)	√		√				√			√	√
(Iakovou, 2001)	√		√				√		√		√
(Persson and Göthe-Lundgren, 2005)	√			√			√				√
(Elkamel et al., 2008)	√					√		√			√
(Kuo and Chang, 2008a)	√			√				√			√
(Al-Qahtani and Elkamel, 2008a)	√			√				√		√	√
(Kim et al., 2008)	√					√		√		√	√
(MirHassani, 2008)	√			√			√				√
(Al-Qahtani and Elkamel, 2009)	√			√			√			√	√
(Guyonnet et al., 2008)	√			√				√		√	√
(Hamedi et al., 2009)		√				√	√				√
(Chen et al., 2010a)	√			√			√			√	
(Fernandes et al., 2011)	√			√			√			√	√
(Fernandes et al., 2013a)	√			√				√		√	√
(Fiorencio et al., 2015)	√			√			√			√	√
(Kazemi and Szmerekovsky, 2015b)	√			√			√			√	√

***Keys for Table 2.1**

LP	:	Linear Programming	MNLP	:	Mixed Integer Non-linear Programming
MILP	:	Mixed Integer Programming	CM	:	Cost minimization
NLP	:	Non-linear Programming	PM	:	Profit maximization

2.3 Stochastic and Risk Models

Hydrocarbon companies are affected by many uncertain parameters including fluctuating prices, yields, and demand, etc. Therefore, there is a need to study the effect of uncertainty on the HCSC decisions through stochastic models that incorporate uncertainty. In this section, the research papers that discuss HCSC supply chains under uncertainty will be reviewed.

Regarding oil-supply chain models, the first study in this field was done by (Escudero et al., 1999) who formulated a two-stage stochastic programming model for a multi-period supply chain. The model addressed downstream oil supply chain starting from supplying crude to refineries up to distributions. The model determined refining and distribution-scheduling activities under uncertainties on demand, cost of supply, and refined oil prices. (Dempster et al., 2000) formulated a two-stage stochastic planning model for the oil supply chain. The oil supply chain consists of all activities related to crude oil supply, transformation and distribution scheduling. The oil supply chain comprises crude oil depot and refinery. A deterministic linear model was used as the basis for implementing the stochastic programming formulation. The tactical model was formulated for an oil supply chain under uncertain demand and supply cost.

(Lababidi et al., 2004) developed a two-stage stochastic approach for integration of petrochemical supply chain with local refineries under uncertainties of demand, prices, costs of supply and production. The petrochemical sector compromises of production site with reactors for producing hexene and catalysts, whereas ethane was obtained from a local refinery. The model considered importing hexene and catalysts from international markets. (Al-Othman et al., 2008) developed an integrated two-stage stochastic MILP model with uncertainties arising from market demands and prices. Three scenarios are considered for demand and prices, above average, average, or below average. In the first stage the production quantities are specified for each type of crude oil, while in the second stage the production quantities of refinery and petrochemical products are optimized. The oil supply chain comprises crude oil production, processing at refinery and petrochemicals, and distribution activities.

(Neiro and Pinto, 2005) developed a multipored and tactical MINLP model for optimizing a petroleum production planning addressing fundamental issues related to oil refineries. The model studied the uncertainty of both crude oil and product prices and demands. The objective function contained a nonlinear operating cost term as a result of the unit operating mode and inlet stream flow rate. (MirHassani, 2008) developed a two-stage stochastic linear programming model for operational planning of a petroleum supply chain capacitated network between refineries and depots to minimize total inventory and transportation costs under uncertain demand. He studied the effect of transportation capacity on demand fulfillment. The model composed of a set of petroleum refineries, some multi-product pipelines, different transportation facilities and several depots that are connected to regions as well as pump stations.

(Ghatee and Hashemi, 2009) developed a stochastic model considering daily production of each unit in supply chain, daily exportation of each port, refinery intake, capacity of pipelines, and capacity of storage tanks. (Carneiro et al., 2010a) formulated a two stage scenario based stochastic programming model incorporating CVaR a risk measure. The aim of the model is to manage the risk in the portfolio optimization; the objective is to maximize the expected portfolio return (i.e., the weighted mean of the individual returns). (Al-Qahtani and Elkamel, 2010) extended the deterministic model of (Al-Qahtani and Elkamel, 2008b) by incorporating uncertainties in crude supply and final products demand and prices. The stochastic model was formulated as a two-stage stochastic MILP problem whereas the robust optimization was formulated as an MINLP problem with nonlinearity arising from modeling the risk components. Furthermore, the sample average approximation (SAA) was applied to generate the required samples. They considered crude oil processing at refineries and marketing of refined oil refined products locally and internationally, and imports of refined oil products.

(Li et al., 2004) proposed two tactical programming models; two-stage and chance-constraint models to refinery planning considering uncertainties in demand and supply. Their model contains two service objectives: confidence level (i.e. probability of satisfying customer demand) and fill rate (i.e. proportion of demand that met by a plant). The model considered optimizing production rate of a single oil product at refinery and flow quantity of oil to final customer. (Khor et al., 2008) developed two-stage stochastic model and stochastic robust programming model to optimize production operation of a refinery. The models considered transforming of crude oil at refinery and the flow of the oil to the final customer. The model tackled and incorporated risk management for an optimal planning and addressed uncertainties in prices of crude oil, refined products, refined products demand, and refined products yields. The variance was adopted as the risk measure.

(Oliveira and Hamacher, 2012) developed a strategic stochastic programming model for distribution of petroleum products under demand uncertainty. The proposed logistics network consists of a set of nodes (international markets, refineries, terminals, and bases) that are connected by transportation arcs. The proposed model did not consider the processing of crude oil and the importation of products. (Oliveira et al., 2013) developed a multi-period stochastic investment planning model considering network design and capacity expansion under demand uncertainty. The considered network compromises of supply nodes, primary and secondary bases. The model built a decision making tool to optimize transportation and inventory decisions while minimizing investment and expected logistics costs.

(Ribas et al., 2010) formulated three stochastic models for strategic decision making; two-stage stochastic model, robust min–max regret model, and max–min model to cope with crude oil production, demand for refined products and market prices random parameters. A comparison was conducted for performance of the three models. The proposed model comprises refineries, petrochemical plants, which also produce refined products. And it considered local, international supply of crude oil, natural gas and vegetable oil to the refinery. (Leiras et al., 2010) extended (Ribas et al., 2010) model and (Al-Qahtani and Elkamel, 2008b) model to account for the uncertainties in material supplies cost and final product price. The model investigated the strategic planning decisions related to refineries integration. (Yang et al., 2010) utilized Markov chain to represent the fluctuation of product yield of refineries. They used chance constraint programming in the formulation. (Tong et al., 2012) incorporated conditional value at risk (CVaR) as a risk averse term in the objective function, and estimated the threshold value by Sample Average Approximation (SAA). (Fernandesa et al., 2015) developed a stochastic MILP model to maximize the expected net present value (ENPV) based on demand uncertainty.

Regarding gas-supply chain models, only one paper studied the gas supply chain model. (Azadeh et al., 2015a) presented the uncertainty of demand, capacity, and costs as a fuzzy parameters for minimizing the total costs and environmental costs. The model was solved through two steps first by getting the deterministic equivalent, and second by converting the model into a single objective. Until now, no study on modeling oil and gas supply chain in a single model under uncertainty.

Table 2.2 Summary of the selected stochastic and risk papers.

Reference	Network		Decision levels		Modelling Approaches				Performance measure			Uncertain Parameters				Risk
	Oil	Gas	Strategic	Tactical	LP	MLP	NLP	MNLP	CM	PM	Other	Price	Demand	Yield	Others	
(Escudero et al., 1999)	√			√	√				√			√	√			
(Dempster et al., 2000)	√			√	√				√			√	√			
(Li et al., 2004)	√			√		√					√	√	√			
(Neiro and Pinto, 2005)	√			√				√		√		√	√			
(Khor et al., 2008)	√		√	√		√				√		√	√	√		VR
(Al-Qahtani et al., 2008)	√		√	√				√	√			√	√	√		VR
(Al-Othman et al., 2008)	√			√		√				√		√	√			
(Ghatee and Hashemi, 2009)	√		√	√		√			√				√			
(J. Jiao et al., 2010)	√			√	√				√			√	√			
(Al-Qahtani and Elkamel, 2010)	√		√	√		√			√			√	√			VR
(Yang et al., 2009)	√			√		√			√					√		
(Leiras et al., 2010)	√		√	√		√			√			√	√			
(Carneiro et al., 2010)	√		√	√		√				√		√	√			CR
(Ribas et al., 2010)	√			√		√				√		√	√			CR
(Ribas et al., 2011)	√			√	√					√		√	√			
(Tong et al., 2011)	√			√		√			√				√	√		CR

Table 2.2 continue...

Reference	Network		Decision levels		Modelling Approaches				Performance measure			Uncertain Parameters				Risk
	Oil	Gas	Strategic	Tactical	LP	MLP	NLP	MNLP	CM	PM	Other	Price	Demand	Yield	Others	
(MirHassani and Noori, 2011)	√			√		√			√				√			
(Tong et al., 2012)	√			√		√			√				√	√	√	
(Oliveira and Hamacher, 2012)	√		√	√		√			√				√			
(Oliveira et al., 2013)	√		√	√		√			√				√			ES
(Fernandes et al., 2014)	√		√	√		√				√			√			
(Fernandesa et al., 2015)	√		√	√		√			√				√			
(Azadeh et al., 2015b)		√		√	√				√		√		√		√	
(Liqiang and Guoxin, 2015)	√		√	√		√			√			√				
Dissertation	√	√		√	√				√		√	√	√			CR

***Keys for Table 2.2**

LP	:	Linear Programming	MNLP	:	Mixed Integer Non-linear Programming	ES	:	Expected shortage
MILP	:	Mixed Integer Programming	CM	:	Cost minimization	CR	:	CVaR
NLP	:	Non-linear Programming	PM	:	Profit maximization	VR	:	Variance

Within the few research works that considered environmental legislation; (Liqiang and Guoxin, 2015) proposed a model oriented around CO_2 emissions. They mitigate the carbon emissions through minimizing the taxes from environment legislation. Table 2.2 summarizes the literature in terms of type of supply chain, decision level, performance measure, uncertain parameters, and risk attributes.

2.4 Multi-objective Optimization in HCSC

In recent years, researchers have enriched the literature in the HCSC planning and optimization with the purpose of maximization or minimization of a single objective function. Therefore, from the literature, there are only two multi-objective optimization models developed for modeling HCSC ((Iakovou, 2001) and (Azadeh et al., 2015a))

(Iakovou, 2001) dealt with long term decisions of maritime transportation to minimize the transportation and risk costs. The problem is formulated as a multi-objective, multi-commodity, multiple origin-destination pairs, and multimodal problem. The output of their model, a network of routes for transporting vessels between different nodes. The model needs to be modified to account for different scenarios in transportation activities (i.e. robust model). (Azadeh et al., 2015a) developed a multi-objective and multi-period model for natural gas supply chain to consider both economic and environmental objectives. The model considered the uncertainties in demand, capacity and cost of compressor and gas station. The model considered local and import supply of natural gas, refinery, compressor station, storage tanks, and final customers.

Therefore, the area of multi-objective optimization in HCSC has few papers, only two and need more research. This is the main motivation for the dissertation. For further reading, a recent review of the literature on the area of applying the mathematical programming to petroleum supply chain was conducted by (Sahebi et al., 2014). Some of their recommendations for future research are: examining both strategic and tactical decisions in an integrated form, nonlinearity of the refineries operations needs more research attention, environmental impact of the petroleum supply chain problems needs more efforts to be well explored, modeling uncertainty features with multi-stage stochastic models, and development of efficient solution techniques for multi-objective function problems. Also, (Leiras et al., 2011) reviewed the literature for the techniques and methodologies used for optimizing refinery operations. They concluded that non-linearity in refining operations have to be considered in more depth, and formulating and solving a stochastic MINLP is a challenging area.

2.5 Conclusion

Table 2.1 and 2.2 classified the literature based on certain attributes. This type of classification is helpful in detecting the key important features of the HCSC and in distinguishing this work from the previous works. Despite of intensive work in the area of HCSC optimization, it is appeared that almost all of papers built a model for either oil or gas supply chains and no research appeared to optimize oil and gas networks in a single supply chain. Also, few studies have attempted the optimization of the HCSC in a multi-dimensional and multi-objective framework, as can be seen in Table 2.1 and Table 2.2. Moreover, the above literature review revealed that the HCSC problem has not been modeled in a multi-objective stochastic optimization framework. Finally, incorporating the risk management into the stochastic multi-objective model has not appeared in the literature. Therefore, this dissertation fills the above mentioned gaps by developing a multi-period, multi-item (i.e., oil and gas simultaneously), and multi-objective mathematical model under the assumption of fixed parameters and uncertain parameters for tactical decision making. Also, the risk associated with uncertain parameters in the stochastic model is quantified and mitigated by employing the CVaR risk measure.

CHAPTER 3

MULTI-OBJECTIVE DETERMINISTIC MODEL

3.1 Introduction

Oil and gas companies play an important role in the global economy. The optimal planning of oil and gas productions is vital to the petroleum producing countries to ensure high support to their economy through distributing and marketing petroleum products locally and/or internationally. The Hydrocarbon Supply Chain (HCSC) is classified into two segments: upstream and downstream. The oil supply chain network comprises oil fields, Oil and Gas Separation Plants (GOSPs), primary storage facilities, oil processing plants, refinery plants, secondary storage facilities, and demand nodes. While natural gas supply chain involves gas fields, storage facilities, gas plants, fractionation plants, secondary storage facilities, and demand nodes. The oil and gas networks overlap in many entities and shares some products. Therefore, it is more beneficial to model the oil and gas networks in an integrated fashion as a single supply chain.

Also, integration of all downstream supply chain entities in a single model leads to effective management of the HCSC. The downstream HCSC has attracted the interest of many researchers due to its central role in the world economy. In recent years, the world has experienced a huge decrease in prices of crude oil, as a result, petroleum producing countries faced budget deficit, and then, some of projects are stopped. Therefore, petroleum producing countries have planned to reduce their oil production to overcome this impairment. However, if they reduce oil production, they would lose market share and could not satisfy gas products demand of industrial plants. Accordingly, the petroleum producing countries have to change their production and marketing plans strategically and tactically considering such variation and within a multi-dimensional framework. These plans must be based on satisfying multiple objectives. The trade-offs between economic goals and service level are important to keep sustain in the market.

Thus, this chapter is concerned with modeling downstream segment of oil and gas supply chain to help and guide decision makers as they build their tactical decisions within a multi-dimensional scope under the assumption of fixed and known parameters. The obtained model is Multi-Objective Deterministic (MOD) model with multi-periods. The multi-objective scope is adopted for modeling the HCCS due to its versatility in providing trade-offs among alternative solutions and because in real life most problems are of multi-dimensional and multi-objective nature.

The selected objectives related to downstream activities are the following: minimize the total cost, maximize the total revenue, and maximize the service level. Minimizing the total cost is intended to reduce costs of production, holding, and transportation of crude oil, natural gas, and their products. Maximizing the total revenue is important for any company to pay its financial commitments and for any national producer to support the country's budget. While maximizing the service level is important for any organization to satisfy their customer needs, and then increase sales and to keep sustain in market. The multi-objective model is a practical tool for assessing the trade-offs among the selected objectives and addressing tactical decisions related to downstream HCSC activities such as: the processing quantities, transforming and fractionating quantities, flows of crude oil, oil refined products, and gas products between each two nodes of the supply chain, imports and exports volumes.

The MOD model is verified and solved using an improved augmented ε-constraint algorithm to generate Pareto optimal solutions. The utility of the proposed model is demonstrated using real case from the Kingdom of Saudi Arabia. Sensitivity analysis is conducted to investigate the effects of key; controlled and uncontrolled parameters on the set of Pareto optimal solutions. The model is expected to have a positive impact on future management of this important component of the energy sector.

The rest of this chapter is organized as follows: Section 3.2 presents the MOD model formulation. Section 3.3 explains oil network and gas network of Saudi Arabia as a case used to validate the three proposed models in this dissertation. In section 3.4, the MOD is solved and the results are explained and discussed. Also, a sensitivity analysis is conducted in section 3.4. The chapter is closed by the conclusion.

3.2 MOD Model Formulation

In this section, the multi-objective deterministic model is formulated for the hydrocarbon supply chain stated in section 1.2.

3.2.1 MOD Model Notations

The sets, subsets, decision variables, and input parameters used in mathematical modeling of hydrocarbon supply chain are outlined below in Table 3.1.

Table 3.1 Notations of the MOD model

Sets	
$i\ ,\ j\ \in I$	All nodes.
h	Set of well head streams.
N	Set of natural gas types.
C	Set of crude oil types.
O	Set of oil refined products.
G	Set of gas products.
T	Set of time periods.
Subsets	
$s, r, b \subseteq I$	Oil processing plants, refinery plants, and bulk plants.
$a, f\ \subseteq I$	Gas plants and fractionation plants.
$e,\ u,\ d \subseteq I$	Demand nodes: local regions, international terminals, and industries
$k \subseteq I$	Import nodes.
$h\ \in H$	Well head stream oil type h: Arabian light, Arabian extra light, Arabian medium, and Arabian heavy.
$c\ \in C$	Crude oil type c: Arabian light, Arabian extra light, Arabian medium, and Arabian heavy.
$o\ \in O$	Oil refined products: LPG, naphtha, gasoline, diesel, kerosene, fuel oil, and asphalt.
$n\ \in N$	Natural gas: associated and non-associated.
$g\ \in G$	Gas products: natural gas liquid, methane, ethane, propane, butane, natural gasoline, and hydrogen sulfide.
Decision Variables	
Supply from upstream:	
X_{st}^{h}	Supply of well head stream type h from upstream to oil processing plant s, at time t.
Y_{at}^{n}	Supply of natural gas type n from upstream to gas plant a, at time t.

Production and processing quantity:	
X_{st}^{c}	Amount of crude oil type c sweetened and processed at oil processing plant s at time t.
Y_{at}^{g}	Amount of gas g separated at gas plant a at time period t.
X_{rt}^{o}	Amount of oil refined products o transformed at refinery plant r at time period t.
Y_{ft}^{g}	Amount of gas products g fractionated at fractionation plant f at time period t.

Flow quantity:	
X_{srt}^{c}	Amount of crude oil type c transported from oil processing plant s to refinery plant r at time period t .
X_{sut}^{c}	Amount of crude oil type c transported from oil processing plant s to international terminal u at time period t .
X_{rut}^{o}	Amount of oil refined products o transported from refinery plant r to terminal u at time period t.
X_{rbt}^{o}	Amount of oil refined products o transported from refinery plant r to bulk plant b at time period t.
X_{bet}^{o}	Amount of oil refined products o transported from bulk plant b to domestic region e at time period t.
X_{bdt}^{o}	Amount of oil refined products o transported from bulk plant b to industry d at time period t.
Y_{aut}^{g}	Amount of gas g transported from gas plant a to international terminal u at time period t.
Y_{adt}^{g}	Amount of gas g transported from gas plant a to industry d at time period t.
Y_{aft}^{g}	Amount of gas g transported from gas plant a to fractionation plant f at time period t.
Y_{fut}^{g}	Amount of gas products g transported from fractionation plant f to terminal u at time period t.
Y_{fdt}^{g}	Amount of gas products g transported from fractionation plant f to industry d at time period t.
Y_{fet}^{g}	Amount of gas products g transported from fractionation plant f to t region e at time period t.

Production above and below demand:	
x_{ut}^{c+}, x_{ut}^{c-}	Production of crude oil type c above and below the demand of international market at terminal u at time period t.
X_{ut}^{o+}, X_{ut}^{o-} X_{et}^{o+}, X_{et}^{o-} X_{dt}^{o+}, X_{dt}^{o-}	Production of oil refined products o above and below the demand of terminal u, region e, and industry d at time t.
Y_{ut}^{g+}, Y_{ut}^{g-} Y_{et}^{g+}, Y_{et}^{g-} Y_{dt}^{g+}, Y_{dt}^{g-}	Production of gas products g above and below the demand of terminal u, region e, and industry d at time t.
Service levels:	
SLO_t	Service level of oil products during time period t.
SLG_t	Service level of gas products during time period t.
$MTSL$	A minimum target for the service level, which must be attained for all products at all the time intervals t.
Parameters	
Capacity Parameters:	
AC_{su}	Capacity of routes connecting oil processing plant s with international terminal u.
AC_{sr}	Capacity of routes connecting oil processing plant s with refinery plant r.
AC_{ru}	Capacity of routes connecting refinery plant r with international terminal u.
AC_{rb}	Capacity of routes connecting refinery plant r with and bulk plant b.
AC_{be}	Capacity of routes connecting bulk plant b with domestic region e.
AC_{bd}	Capacity of routes connecting bulk plant b with industry d.
AC_{af}	Capacity of routes connecting gas plant a with fractionation plant f.
AC_{ad}	Capacity of routes connecting gas plant a with industry d.
AC_{au}	Capacity of routes connecting gas plant a with international terminal u.

AC_{fu}	Capacity of routes connecting fractionation plant f with international terminal u.
AC_{fe}	Capacity of routes connecting fractionation plant f with domestic region e.
AC_{fd}	Capacity of routes connecting fractionation plant f with industry d.
CP_s	Capacity of oil processing plant s.
CP_a	Capacity of gas plant a.
CP_r	Capacity of refinery plant r.
CP_f	Capacity of fractionation plant f.
CP_u	Capacity of international terminal u.
Demand Parameters:	
D_{ut}^{c}	Demand for crude oil type c at international terminal u at time t.
D_{et}^{o}	Demand for oil refined products o at region e at time t.
D_{ut}^{o}	Demand for oil refined products o at terminal u at time t.
D_{dt}^{o}	Demand for oil refined products o at industry d at time t.
D_{et}^{g}	Demand for gas products g at region e at time t.
D_{ut}^{g}	Demand for gas products g at terminal u at time t.
D_{dt}^{g}	Demand for gas products g at industry d at time t.
Costs Parameters:	
PC_{st}^{h}	Unit processing cost of well head stream h at oil processing plant s at time t.
PC_{at}^{n}	Unit processing cost of natural gas type n at gas plant a at time t.
SC_{srt}^{c}	Unit transformation cost of oil stream X_{srt}^{c} at refinery plant r at time t.
SC_{aft}^{g}	Unit separation cost of gas stream Y_{aft}^{g} at fractionation plant f at time t.
IC_{kt}^{o}	Unit purchasing cost of imported oil refined products o from import market k at time t.
IC_{kt}^{g}	Unit purchasing cost of imported gas products g from import market k at time t.

CT_{srt}^{c} Unit transportation cost of f oil stream X_{srt}^{c} between oil processing plant s and refinery plant r at time t.

CT_{sut}^{c} Unit transportation cost of f oil stream X_{sut}^{c}between oil processing plant s and terminal u at time t.

CT_{rut}^{o} Unit transportation cost of oil refined products o between refinery plant r and terminal u at time t.

CT_{rbt}^{o} Unit transportation cost of oil refined products o between refinery plant r and bulk plant b at time t.

CT_{bet}^{o} Unit transportation cost of oil refined products o between bulk b and region e at time t.

CT_{bet}^{o} Unit transportation cost of oil refined products o between bulk b industry d at time t.

CT_{aut}^{g} Unit transportation cost of gas products g between gas plant a and terminal u at time t.

CT_{adt}^{g} Unit transportation cost of gas products g between gas plant a industry d at time t.

CT_{aft}^{g} Unit transportation cost of gas products g between gas plant a and fractionation plant f at time t.

CT_{fut}^{g} Unit transportation cost of gas products g between fractionation plant f and terminal u at time t.

CT_{fdt}^{g} Unit transportation cost of gas products g between fractionation plant f industry d at time t.

CT_{fet}^{g} Unit transportation cost of gas products g between fractionation plant f and region e at time t.

HC_{st}^{h} Inventory holding cost of well head h at oil processing plant s at time t.

HC_{at}^{n} Inventory holding cost of natural gas n at gas plant a at time t.

HC_{rt}^{c} Inventory holding cost of crude oil c at refinery plant r at time t.

HC_{bt}^{o} Inventory holding cost of oil refined products o bulk plant b at time t.

HC_{ft}^{g} Inventory holding cost of gas products g at fractionation plant f at time t.

w_{ut}^{c+}, w_{ut}^{c-}	Penalty cost of producing crude oil c above, below the specified demand of terminal u at time t.
w_{ut}^{o+}, w_{ut}^{o-} w_{et}^{o+}, w_{et}^{o-} w_{dt}^{o+}, w_{dt}^{o-}	Penalty cost of producing oil refined products o above, below the specified demand of terminal u, region e, and industry d at time t.
w_{ut}^{g+}, w_{ut}^{g-} w_{et}^{g+}, w_{et}^{g-} w_{dt}^{g+}, w_{dt}^{g-}	Penalty cost of producing gas products g above, below the specified demand terminal u, region e, and industry d at time t.

Selling Prices Parameters:

SP_{ut}^{c}	Selling price of crude oil c at terminal u at time t.
SP_{et}^{o}	Selling price of oil refined products o at region e at time t.
SP_{ut}^{o}	Selling price of oil refined products o at terminal u at time t.
SP_{dt}^{o}	Selling price of oil refined products g at industry d at time t.
SP_{et}^{g}	Selling price of gas products g at region e at time t.
SP_{ut}^{g}	Selling price of gas products g at terminal u at time t.
SP_{dt}^{g}	Selling price of gas products g at industry d at time t.

Yields and OPEC Parameters:

P_{st}^{hc}	Yields of crude oil obtained from input well head stream h to oil processing plant s at time t.
P_{at}^{ng}	Yields of gas products g obtained from input stream n to gas plant a at time t.
P_{srt}^{co}	Yields of oil refined products o obtained from input stream to refinery plant r at time t.
$OPEC_t$	OPEC quota or market share allocated to specific country at time t.
dr	Discount rate per time period t.

3.2.2 MOD Model Constraints

The proposed model optimizes three objectives while satisfying many practical constraints. The constraints are material balance, capacity of processing entities and routes, local customer demand, industry demand, international demand, service level, and OPEC quota constraints.

Material balance constraints: The inputs must equal the outputs for any plant. For each oil processing plant s, crude oil type c at each time period, the yields of crude oil in well head stream h multiplied by the well head stream oil flow to the oil processing plant plus the inventory level from the previous period are enforced by Eq. (3.1) to equal crude oil processing quantity plus the inventory level. Eq. (3.2) balances the processing quantities of crude oil with the output from oil processing plant to refinery plants and international markets.

$$P_{st}^{hc} X_{st}^{h} + X_{st-1}^{h+} = X_{st}^{c} + X_{st}^{h+} \qquad \forall \quad s, c, t \qquad 3.1$$

$$\sum_{r} X_{srt}^{c} + \sum_{u} X_{sut}^{c} = X_{st}^{c} \qquad \forall \quad s, c, t \qquad 3.2$$

The mass balance for gas plant is represented by Eqs.(3.3 & 3.4) . For each gas plant a, gas type, at each time period, the yields of each gas type in the input stream (associated and no-associated natural gas) plus the inventory from the previous period are equal to the processing volume plus the inventory level; Eq. (3.3). Eq. (3.4) equates the processing volume of each gas type with the gas stream directed to fractionation plants, local, industries, and international terminals.

$$\sum_{n} P_{at}^{ng} \, Y_{at}^{b} + \sum_{n} Y_{at-1}^{n+} = Y_{at}^{g} + \sum_{n} Y_{at}^{n+} \qquad \forall \quad a, g, t \qquad 3.3$$

$$\sum_{f} Y_{aft}^{g} + \sum_{d} Y_{adt}^{g} + \sum_{u} Y_{aut}^{g} = Y_{at}^{g} \qquad \forall \quad a, g, t \qquad 3.4$$

Eqs. (3.5 & 3.6) represents the mass balance for refinery plant. The yields of each oil refined product in the input stream to refinery plant plus inventory level from the previous period equal the produced oil refined product plus inventory level; Eq. (3.5). Eq. (3.6) balances the quantity of each oil refined product produced at a refinery plant with the output from that refinery plant to the bulk plants and international markets.

$$\sum_{s,c} P_{srt}^{co} \; X_{srt}^{c} + \sum_{c} X_{rt-1}^{c+} = X_{rt}^{o} + \sum_{c} X_{rt}^{c+} \qquad \forall \quad r, o, t \qquad 3.5$$

$$\sum_{u} X_{rut}^{o} + \sum_{b} X_{rbt}^{o} = X_{rt}^{o} \qquad \forall \quad r, o, t \qquad 3.6$$

The material balance constraints for fractionation plant f are formulated in Eqs. (3.7 & 3.8). The yields of gas products in the NGL input to the fractionation plant plus inventory level from previous period are enforced to equal the fractionated gas product plus inventory level; Eq. (3.7). Eq. (3.8) balances the fractionated quantity of each gas product with the output from the fractionation plant to terminals, regions, and industries demand nodes.

$$\sum_{a} P_{aft}^{g} Y_{aft}^{g} + Y_{ft-1}^{g+} = Y_{ft}^{g} + Y_{ft}^{g+} \qquad \forall \; f, g, t \qquad 3.7$$

$$\sum_{u} Y_{fut}^{g} + \sum_{e} Y_{fet}^{g} + \sum_{d} Y_{fdt}^{g} = Y_{ft}^{g} \qquad \forall \; f, g, t \qquad 3.8$$

Eq. (3.9) represents the material balance at the bulk plant storage. For each bulk plant b, time period, and oil refined products, volume received by bulk plant from all refinery plants and what is left in the inventory from the previous period must equal to the sum of output from the bulk plant plus the inventory level. Where, the bulk plant receives oil refined products from the refinery plant and supplies them to the industries and local customers.

$$\sum_{r} X^{o}_{rbt} + X^{o+}_{bt-1} = \sum_{e} X^{o}_{bet} + \sum_{d} X^{o}_{bdt} + X^{o+}_{bt} \qquad \forall \ b, o, t \qquad 3.9$$

Plant capacity constraints: The input flow to each entity plus what left from previous period are limited by its capacity. The processing capacities of oil processing plants, gas plants, refinery plants, and fractionation plants, are defined in Eqs.(3.10 - 3.11), respectively.

$$X^{h}_{st} + X^{h+}_{st-1} \leq CP_s \qquad \forall \ s, t \qquad 3.10$$

$$\sum_{n} Y^{n}_{at} + \sum_{n} Y^{n+}_{at-1} \leq CP_a \qquad \forall \ a, t \qquad 3.11$$

$$\sum_{s,c} X^{c}_{srt} + \sum_{c} X^{c+}_{rt-1} \leq CP_r \qquad \forall \ r, t \qquad 3.12$$

$$\sum_{a,g} Y^{g}_{aft} + \sum_{g} Y^{+g}_{ft-1} \leq CP_f \qquad \forall \ f, t \qquad 3.13$$

The capacity limits of international oil and gas terminals are formulated in Eqs. (3.14 & 3.15).

$$\sum_{r,o} X^{o}_{rut} + \sum_{s,c} X^{c}_{sut} \leq \mathrm{CP}_u \qquad \forall \ u, t \qquad 3.14$$

$$\sum_{a,g} Y_{aut}^{g} + \sum_{f,g} Y_{fut}^{g} \leq CP_u \quad \forall\ u,t \qquad 3.15$$

Route capacity constraints: The flow in each route is limited by capacity of route. The constraints for each route in the stated network are represented by Eqs.(3.16-3.29).

$$X_{sut}^{c} \leq AC_{su} \quad \forall\ s,u,c,t \qquad 3.16$$

$$X_{srt}^{c} \leq AC_{sr} \quad \forall\ s,u,c,t \qquad 3.17$$

$$X_{rut}^{o} \leq AC_{ru} \quad \forall\ r,u,o,t \qquad 3.18$$

$$X_{rbt}^{o} \leq AC_{rb} \quad \forall\ r,b,o,t \qquad 3.19$$

$$X_{bet}^{o} \leq AC_{be} \quad \forall\ b,e,o,t \qquad 3.20$$

$$X_{bdt}^{o} \leq AC_{bd} \quad \forall\ b,d,o,t \qquad 3.21$$

$$X_{kut}^{o} \leq AC_{ku} \quad \forall\ k,u,o,t \qquad 3.22$$

$$Y_{aft}^{g} \leq AC_{af} \quad \forall\ a,f,g,t \qquad 3.23$$

$$Y_{adt}^{g} \leq AC_{ad} \quad \forall\ a,n,g,t \qquad 3.24$$

$$Y_{aut}^{g} \leq AC_{au} \quad \forall\ a,u,g,t \qquad 3.25$$

$$Y_{fet}^{g} \leq AC_{fe} \quad \forall\ f,e,g,t \qquad 3.26$$

$$Y_{fdt}^{g} \leq AC_{fd} \quad \forall\ f,d,g,t \qquad 3.27$$

$$Y_{fut}^{g} \leq AC_{fu} \quad \forall\ f,u,g,t \qquad 3.28$$

$$Y_{kut}^{g} \leq AC_{ku} \quad \forall\ k,u,g,t \qquad 3.29$$

Demand constraints: The flow quantity of each product plus below production and minus above production are used to satisfy demand at each demand node. The above and below productions are used as dummy variables to avoid infeasibility. The production above demand is assumed to be kept in the inventory and the production below demand is the quantity that must be satisfied from any market. Eq. (3.30) represents the international demand for crude oil type c at international terminal u.

$$\sum_{s} X_{sut}^{c} - X_{ut}^{c+} + X_{ut}^{c-} \quad = \quad D_{ut}^{c} \qquad \forall\ u,c,t \qquad 3.30$$

Eqs. (3.31-3.33) represent domestic, industry and international demands for oil refined products, respectively.

$$\sum_{b} X_{bet}^{o} - X_{et}^{o+} + X_{et}^{o-} \quad = \quad D_{et}^{o} \qquad \forall\ e,o,t \qquad 3.31$$

$$\sum_{b} X_{bdt}^{o} - X_{dt}^{o+} + X_{dt}^{o-} \quad = \quad D_{dt}^{o} \qquad \forall\ d,o,t \qquad 3.32$$

$$\sum_{r} X_{rut}^{o} - X_{ut}^{o+} + X_{ut}^{o-} \quad = \quad D_{ut}^{o} \qquad \forall\ u,o,t \qquad 3.33$$

The domestic, industry, and international demands for gas products are represented by Eqs. (3.34-3.36), respectively.

$$\sum_{f} Y_{fet}^{g} + \sum_{u} Y_{uet}^{g} - Y_{et}^{g+} + Y_{et}^{g-} \quad = \quad D_{et}^{g} \qquad \forall\ e,g,t \qquad 3.34$$

$$\sum_{a} Y_{adt}^{g} + \sum_{f} Y_{fdt}^{g} + \sum_{u} Y_{udt}^{g} - Y_{dt}^{g+} + Y_{dt}^{g-} \quad = \quad D_{dt}^{g} \qquad \forall\ d,g,t \qquad 3.35$$

$$\sum_{a} Y_{aut}^{g} + \sum_{f} Y_{fut}^{g} - Y_{ut}^{g+} + Y_{ut}^{g-} \quad = \quad D_{ut}^{g} \qquad \forall\ u,g,t \qquad 3.36$$

OPEC quota constraint: The amount of international sales of crude oil of all types are limited by the OPEC quota specified to each country at any period of time; Eq. (3.37).

$$\sum_{s,u,c} X_{sut}^{c} \quad \leq \quad OPEC_t \qquad \forall\ t \qquad 3.37$$

Service level constraints: service level at any time interval is defined for oil and gas products separately as the sales at demand nodes after subtracting the above production quantities divided by the total demand; Eq. (3.38) and Eq.(3.39), respectively:

$$SLO_t = \frac{\sum_{s,u,c}[X_{sut}^{c} - X_{ut}^{c+}] + \sum_{r,u,o}[X_{rut}^{o} - X_{ut}^{o+}] + \sum_{b,e,o}[X_{bet}^{o} - X_{et}^{o+}] + \sum_{b,d,o}[X_{bdt}^{o} - X_{dt}^{o+}]}{\sum_{u,c} D_{ut}^{c} + \sum_{u,o} D_{ut}^{o} + \sum_{e,o} D_{et}^{o} + \sum_{d,o} D_{dt}^{o}} \qquad \forall\ \mathrm{t} \qquad 3.38$$

$$SLG_t = \frac{\sum_{a,d,g}\left[Y_{adt}^{g} - Y_{dt}^{g+}\right] + \sum_{a,u,g}\left[Y_{aut}^{g} - Y_{ut}^{g+}\right] + \sum_{f,e,g}\left[Y_{fet}^{g} - Y_{et}^{g+}\right] + \sum_{f,d,g}\left[Y_{fdt}^{g} - Y_{dt}^{g+}\right] + \sum_{f,u,g}\left[Y_{fut}^{g} - Y_{ut}^{g+}\right]}{\sum_{d,g} D_{dt}^{g} + \sum_{u,g} D_{ut}^{g} + \sum_{e,g} D_{et}^{g}} \qquad \forall \mathrm{t} \qquad 3.39$$

From the above relation, service level depends on time interval and product type. To overcome this problem, a new decision variable is defined called a minimum target for the service level (*MTSL*), and the model then maximizes the minimum value of service level of either oil or gas at any time period; Eqs. (3.40 & 3.41).

$$MTSL\ \leq SLO_t \qquad \forall t \in\ T \qquad 3.40)$$

$$MTSL\ \leq SLG_t \qquad \forall\ t \in T \qquad 3.41$$

3.2.3 MOD Model Objective Functions

The model has three objective functions. The first objective is the total cost over the planning horizon, formulated below:

$$
\begin{aligned}
\text{Minimize } f1 = \sum_{t=1}^{T} (1+dr)^{-(t-1)} \Bigg[& \sum_{s,h,t} PC_{st}^{h} X_{st}^{h} + \sum_{a,n,t} PC_{at}^{n} Y_{at}^{n} + \sum_{s,r,c,t} SC_{srt}^{c}\, X_{srt}^{c} \\
& + \sum_{a,f,g,t} SC_{aft}^{g} Y_{aft}^{g} + \sum_{s,u,c,t} CT_{sut}^{c} X_{sut}^{c} + \sum_{s,r,c,t} CT_{srt}^{c} X_{srt}^{c} + \sum_{r,u,o,t} CT_{rut}^{o}\, X_{rut}^{o} \\
& + \sum_{r,b,o,t} CT_{rbt}^{o}\, X_{rbt}^{o} + \sum_{b,e,o,t} CT_{bet}^{o}\, X_{bet}^{o} + \sum_{b,d,o,t} CT_{bdt}^{o}\, X_{bdt}^{o} \\
& + \sum_{k,u,o,t} CT_{kut}^{o}\, X_{kut}^{o} + \sum_{a,f,g,t} CT_{aft}^{g} Y_{aft}^{g} + \sum_{a,u,g,t} CT_{aut}^{g} Y_{aut}^{g} \\
& + \sum_{a,d,g,t} CT_{adt}^{g} Y_{adt}^{g} + \sum_{f,u,g,t} CT_{fut}^{g} Y_{fut}^{g} + \sum_{f,d,g,t} CT_{fdt}^{g} Y_{fdt}^{g} + \sum_{f,u,g,t} CT_{fut}^{g} Y_{fut}^{g} \\
& + \sum_{f,e,g,t} CT_{fet}^{g} Y_{fet}^{g} + \sum_{k,u,g,t} CT_{kut}^{g} Y_{kut}^{g} + \sum_{k,u,o,t} IC_{kt}^{o}\, X_{kut}^{o} + \sum_{k,u,g,t} IC_{kt}^{g} Y_{kut}^{g} \\
& + \sum_{s,h,t} HC_{st}^{h}\, X_{st}^{h+} + \sum_{a,n,t} HC_{at}^{n}\, Y_{at}^{n+} + \sum_{r,c,t} HC_{rt}^{c}\, X_{rt}^{c+} + \sum_{b,o,t} HC_{bt}^{o}\,,\, X_{bt}^{o+} \\
& + \sum_{f,g,t} HC_{ft}^{g}\, Y_{ft}^{g+} + \sum_{e,o,t} (w_{et}^{o+} X_{et}^{o+} + w_{et}^{o-} X_{et}^{o-}) \\
& + \sum_{d,o,t} (w_{dt}^{o+} X_{dt}^{o+} + w_{dt}^{o-} X_{dt}^{o-}) + \sum_{u,o,t} (w_{ut}^{o+} X_{ut}^{o+} + w_{ut}^{o-} X_{ut}^{o-}) \\
& + \sum_{e,g,t} \left(w_{et}^{g+} Y_{et}^{g+} + w_{et}^{g-} Y_{et}^{g-}\right) + \sum_{d,g,t} \left(w_{dt}^{g+} Y_{dt}^{g+} + w_{dt}^{g-} Y_{dt}^{g-}\right) \\
& + \sum_{u,g,t} \left(w_{ut}^{g+} Y_{ut}^{g+} + w_{ut}^{g-} Y_{ut}^{g-}\right) + \sum_{u,c,t} (w_{ut}^{c+} X_{ut}^{c+} + w_{ut}^{c-} X_{ut}^{c-}) \Bigg]
\end{aligned}
$$

Total costs comprise processing costs of crude oil at oil processing plants and separation cost of natural gas at gas plants, cost of transforming crude oil at refinery plants, cost of fractioning natural gas liquid at fractionation plants, cost of transporting crude oil, oil refined products, and gas products, purchasing cost of oil and gas products from import nodes, inventory holding cost, and penalty cost of over and under the specified demands of crude oil, oil and gas products at demand nodes. The total cost discounted back to its present value based on discount rate *dr* per planning period *t*.

The second objective is the total revenue, formulated below as the selling prices multiplied by the sales of crude oil, and oil and gas products subtracting the over-production quantities.

$$Maximize \quad f2$$

$$\begin{aligned}
&= \sum_{t=1}^{T} (1+dr)^{-(t-1)} \Bigg[\sum_{s,u,c,t} SP_{ut}^{c} (X_{sut}^{c} - X_{ut}^{c+}) \\
&+ \sum_{r,u,o,t} SP_{ut}^{o} (X_{rut}^{o} - X_{ut}^{o+}) + \sum_{b,e,o,t} SP_{et}^{o} (X_{bet}^{o} - X_{et}^{o+}) \\
&+ \sum_{b,d,o,t} SP_{dt}^{o} (X_{bdt}^{o} - X_{dt}^{o+}) + \sum_{a,u,g,t} SP_{ut}^{g} \left(Y_{aut}^{g} - Y_{ut}^{g+} \right) \\
&+ \sum_{a,d,g,t} SP_{dt}^{g} \left(Y_{adt}^{g} - Y_{dt}^{g+} \right) + \sum_{f,u,g,t} SP_{ut}^{g} \left(Y_{fut}^{g} - Y_{ut}^{g+} \right) \\
&+ \sum_{f,d,g,t} SP_{dt}^{g} \left(Y_{fdt}^{g} - Y_{dt}^{g+} \right) + \sum_{f,e,g,t} SP_{et}^{g} \left(Y_{fet}^{g} - Y_{et}^{g+} \right) \Bigg]
\end{aligned}$$

The third objective is the customer service level. It is to maximize the minimum service level of either oil or gas at any time period.

$$Maximize\, f_3 = MTSL$$

3.3 Real Case Study: Kingdom of Saudi Arabia HCSC

Kingdom of Saudi Arabia HCSC is selected as a real case to study the utility of the three developed models. For easy representation, the downstream HCSC network is divided into two networks. Fig. 3.1 depicts the oil network and Fig. 3.2 represents the natural gas network. It is a representation of the figure from McMurra (2011). The whole supply chain network starts from oil processing plants and gas plants and ends at market nodes. The network considers data availability provided by Arabian American Oil Company (ARAMCO).

Four types of well head stream (Arabian light, Arabian extra light, Arabian medium, and Arabian heavy) produced at upstream segments of the HCSC are transported to eight (8) oil processing plants via pipelines. Each oil processing plant receives and sweetens one type of well head stream oil. After processing and removing sulfur at oil processing plants, the crude oil is transported to three (3) main international terminals to satisfy the international demand as constrained by the OPEC quota.

Part of the crude oil that exits from oil processing plants are used to satisfy the local demand of nine (9) local refinery plants. At refinery plants, the crude oil is transformed into seven (7) oil refined products based on their yields (LPG, naphtha, gasoline, diesel, kerosene, fuel oil, and asphalt). The oil refined products are then routed to and stored at seventeen (17) bulk plants (each bulk plant is located close to its demand nodes) and distributed to satisfy local customers demand of the main five (5) regions in the Kingdom, and three (3) large industrial cities. Some of the oil refined products such as LPG, naphtha, and fuel oil are used to satisfy the international demand through terminals. To overcome the shortage in local demand of Kingdom, gasoline and diesel are imported from international markets.

On the other side, the associated and non-associated natural gas streams from gas oil separation plants (GOSPs) and gas fields, respectively, are transported to nine (9) gas plants for impurities removal and recovery of hydrogen sulfide. The output gases are NGL and Methane. The NGL is then piped to five (5) fractionation plants for further separation and fractionation into gas products (ethane, butane, propane, and natural gasoline). Some of NGL is exported through international terminals to satisfy the international demand. All methane and ethane quantities are used to satisfy the local demand of three (3) main industrial cities. While, propane, butane, and natural gasoline are used to fulfill the demand of international and local customers. Some of the ethane is imported from international market to cover the shortage in meeting demand of industrial cities.

First, the MOD model is verified using a single product and small network consisting of one oil processing plant, two (2) refinery plants, one gas plant, two (2) fractionation plants and one demand node for each demand type. Then, the model is used for the full case study.

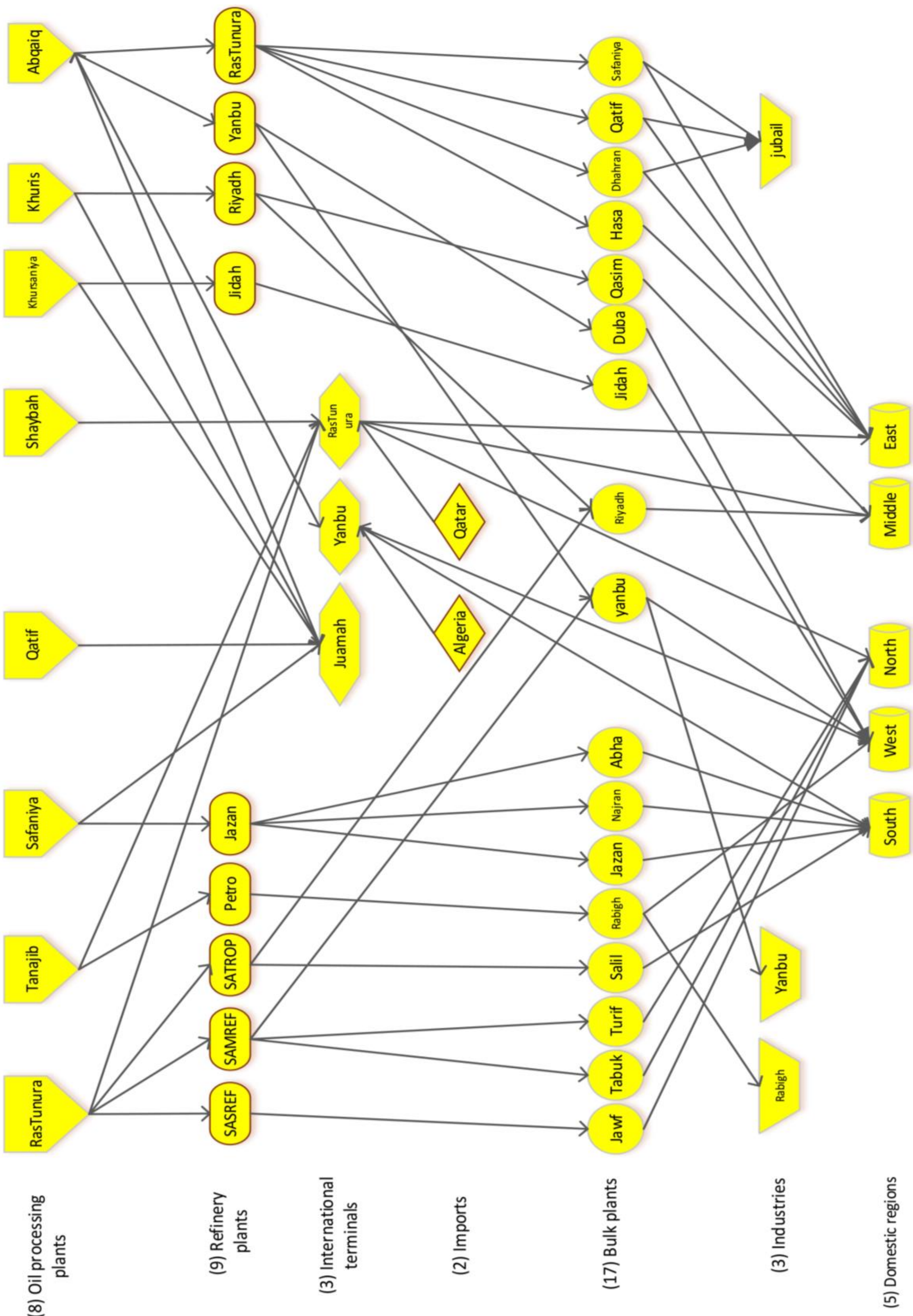


Figure 3.1 Oil network in Saudi Arabia

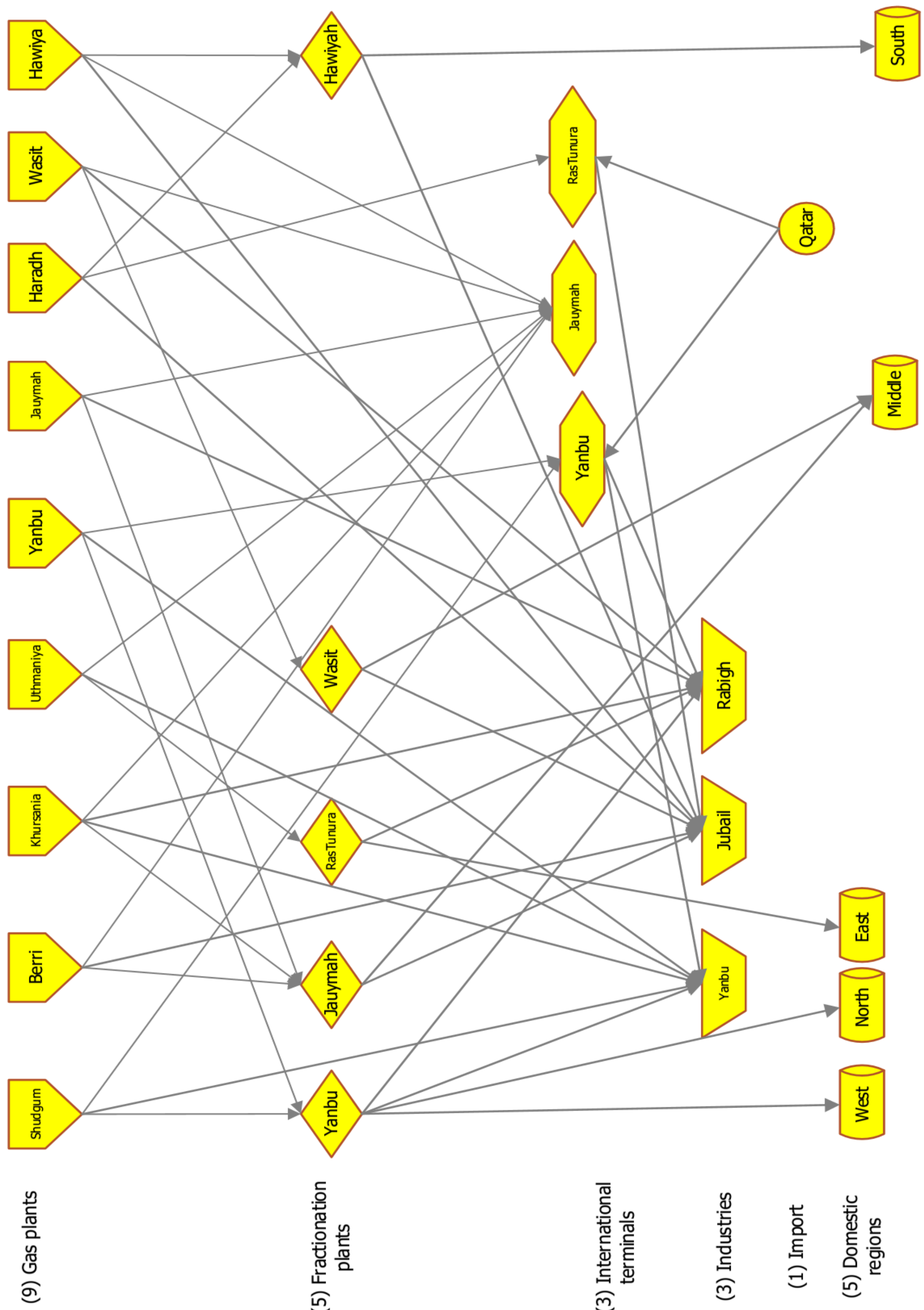


Figure 3.2 Natural gas network in Saudi Arabia

Real and most recent data are collected from many publications; (Duffuaa et al. 1992), (Al-Saleh et al. 1991), (“Facts and Figures” 2017) (“Saudi Arabia Oil & Gas Report” 2017), (“OPEC Annual Statistical Bulletin” 2017) (“Sector Report – Oil and Gas” 2017) (“General Authority for Statistics” 2017) and (“U.S. Energy Information Administration (EIA)” 2017)) (Available in the Appendix) and are used as input to the three proposed models. The required data includes:

1) Yields of main components such as well stream oil composition at oil processing plants, natural gas composition at gas plants and fractionation plants, and crude oil composition at refinery plants.
2) Demand of crude oil, oil refined products, and gas products by local customer, industry and international markets and the corresponding prices. We assume that the demand of each specific region of Kingdom of Saudi Arabia is proportional to its population.
3) International market share specified by the OPEC quota for Kingdom.
4) Capacity of production and storage entities and capacity of routes connecting any two nodes in the HCSC.
5) Processing costs, transportation costs, holding costs, and purchasing costs of imports.
6) The penalty costs of producing above and below the demands. Where, the penalty cost of producing above demands are estimated to equal the holding cost and are estimated to be 25% of the international prices. While the penalty costs of producing below the demands are the cost of satisfying the demand from the international market plus transporting the required quantity to the customer which are estimated to be 125% of the international prices.

The model was run with a planning horizon of three (3) months with a one-month planning period which represents the length of time period for which Saudi Arabia sign the contracts without considering discount rate. However, to demonstrate the utility of the model, the model is run for 6 months planning horizon considering discount rate of 2% per month.

3.4 Applied Case Study: MOD Model

The MOD based on the above data has been solved using improved augmented ε-constraint algorithm proposed by (Mavrotas & Florios 2013). The improved augmented ε-constraint algorithm is adopted and applied in the GAMS 24.1.2 -32 bit (General Algebraic Modeling System) from (Brook et al. 1988) to solve the proposed multi-objective model using the CPLEX 13.3 commercial solver. The CPLEX solver is a computational system designed for solving linear programming and mixed linear programming problems to global optimality. A PC type intel (R) Core (TM)2 Quad CPU processor with 2.67 GHz and 4 GB RAM was used for all computations described in this dissertation. The MOD model statistic are illustrated in Table 3.2.

Table 3.2 MOD model statistics

Blocks of Equations	72	Single Equations	1902
Blocks of Variables	51	Single Variables	3135
CPU time (s)	100	Non-zero Elements	12452

3.4.1 Results and Discussion of MOD Model

In this section, the obtained Pareto optimal solutions along with their corresponding tactical decisions for the developed MOD model are analyzed. Table 3.3 summarizes the payoff results obtained by the lexicographic optimization of the three objectives, as follows. First, the problem is optimized as a single objective problem, i.e minimizing the total cost f_1^*(6736). Then, the total revenue f_2^*(41515) is optimized by adding the obtained total cost value as a constraint to the feasible region, consequently, the service level f_3^*(0.879) is optimized by adding the obtained total cost and revenue values as a constraint. The same procedure is repeated considering total revenue and service level; second and third rows, respectively.

Table 3.3 Payoff results of the three objectives

	Total cost ($ M/3 months)	Total revenue ($ M/3 months)	Service level
Minimize total cost	6736	41515	0.879
Maximize total revenue	7677	41714	0.937
Maximize service level	6895	41558	0.965

After obtaining the payoff table, the Pareto optimal solutions are generated using a systematic search based on dividing the range of the total revenue and service level objectives equidistantly into a 100 grids for (i.e., 101x101 = 10201 possible points). The 100 segments were specified base on conducting a sensitivity analysis by dividing the range of the last two objectives by 25 equidistant segments (26 points) and keep increasing resolution by 25. A new efficient points were added. Values of the three objectives were normalized on the range (0, 1), then, the Euclidean distance between the new points and the old points were calculated. The procedure was continued until the maximum Euclidean distance became less than 0.05 for the 100 grids.

Fig. 3.3 represents the Pareto optimal solutions of the three objectives. The decision maker has to select the preferred plan based on his/her preferred criteria. The best plan gives high total revenue of $ 41714 M/3 months and high service level of 0.937, but with the penalty of high total cost of $ 7677 M/3 months. The worst plan gives low values for total revenue of $ 41515 M/3 months, service level of 0.879, and a total cost of $ 6736 M/3 months. Therefore, a low total cost and a high total revenue cannot be achieved. Consequently, there is a big trade-off between the three objectives.

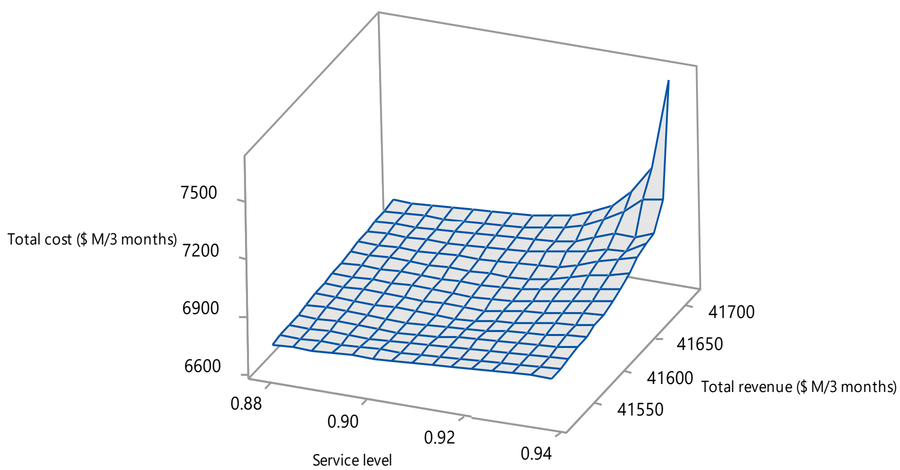


Figure 3.3 3D Pareto curve for MOD model

To shows the trade-offs between the three objectives, two objectives are plotted considering the remaining objective as constraint. Fig. 3.4 shows the relationship between total revenue and total cost at different values of service level. It is clear that as total cost increases total revenue increases and if the decision maker selects the plan that gives high total revenue, he will face an increase in total cost. On the other hand, if the plan with low total cost is selected, it means low total revenue will be obtained. Thus, there is a conflict between total cost and total revenue.

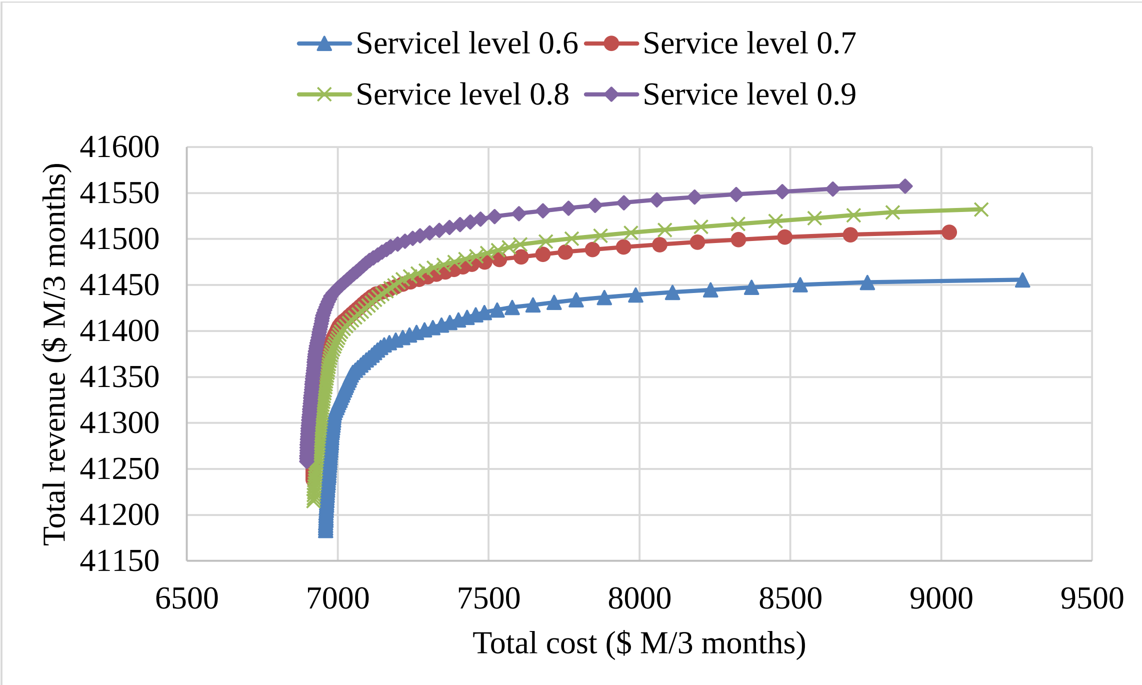


Figure 3.4 Pareto curve between total cost and total revenue at different values of service level

Fig.3.5 shows the trade-off between total revenue and service level at different values of total cost. As service level increases, total revenue increases.

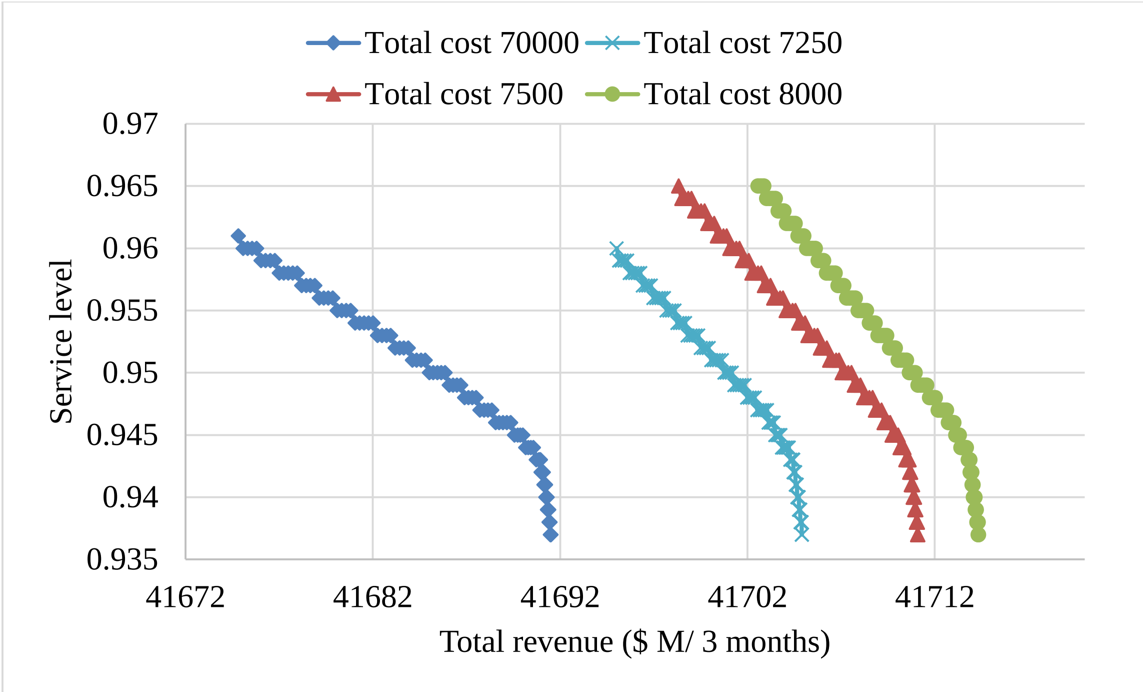


Figure 3.5 Pareto curve between service level and total revenue at different values of total cost

Fig.3.6 shows the trade-off between total cost and service level at different values of total revenue. It is shown that, as service level increases, total cost increases. Consequently, there is a big trade-off between the three objectives.

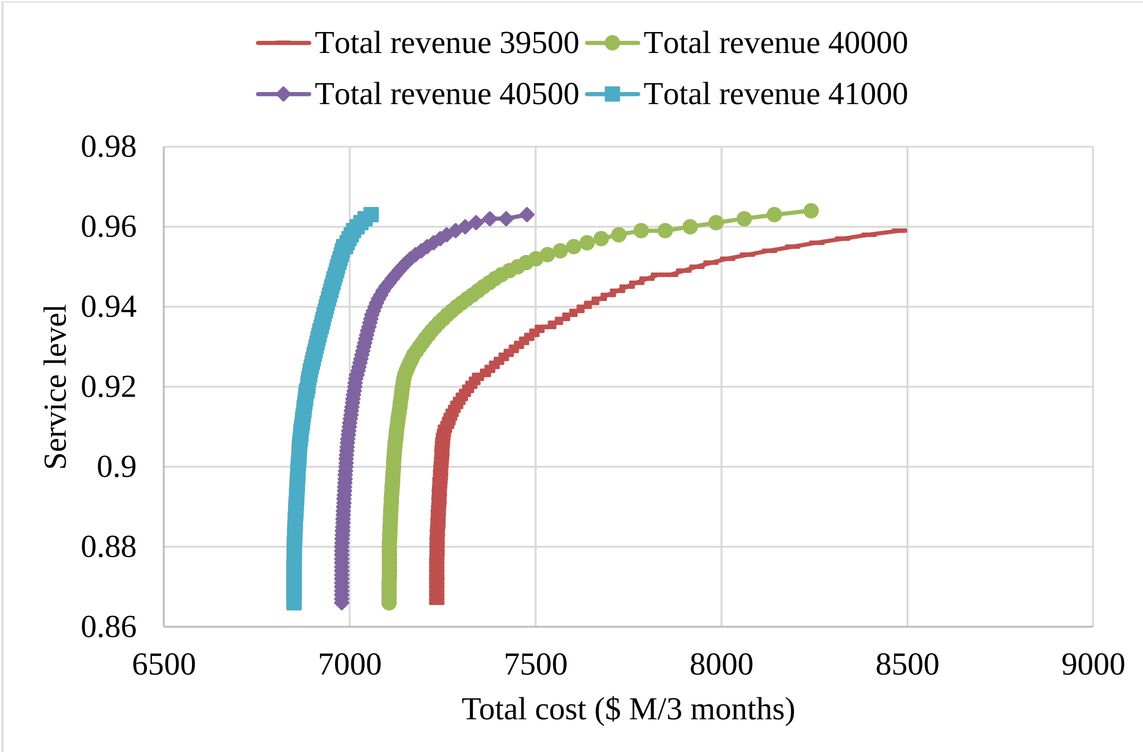


Figure 3.6 Pareto curve between service level and total cost at different values of total revenue

The Pareto optimal curve of both total cost and total revenue with service level is represented in Fig. 3.7. Generally, as service level increases, total cost and total revenue increase. The increases in the total revenue mean more sales at demand nodes which lead to high customer service level. The increases in the sales encourage the companies to produce more which leads to high processing, holding, and transportation costs.

As shown in Fig. 3.7, same service level values are obtained for different values of total cost and total revenue. This variation is because the service level objective function maximizes the minimum value of either oil or gas service level. This fact is clarified clearly from Table 3.4 (sample set of Pareto optima). For example, same service level (0.900, 0.900) is recorded in rows 3 and 4 but with different values of total cost ($ 6743 M/3 months, $ 6748 M/3 months) and total revenue ($41555 M/3 months, $ 41575 M/3 months), respectively. The different values of total cost and total revenue are due to variations in service level of gas at the first and second time periods. The higher service level values indicate that Saudi Arabia has sufficient resources to satisfy customer demands.

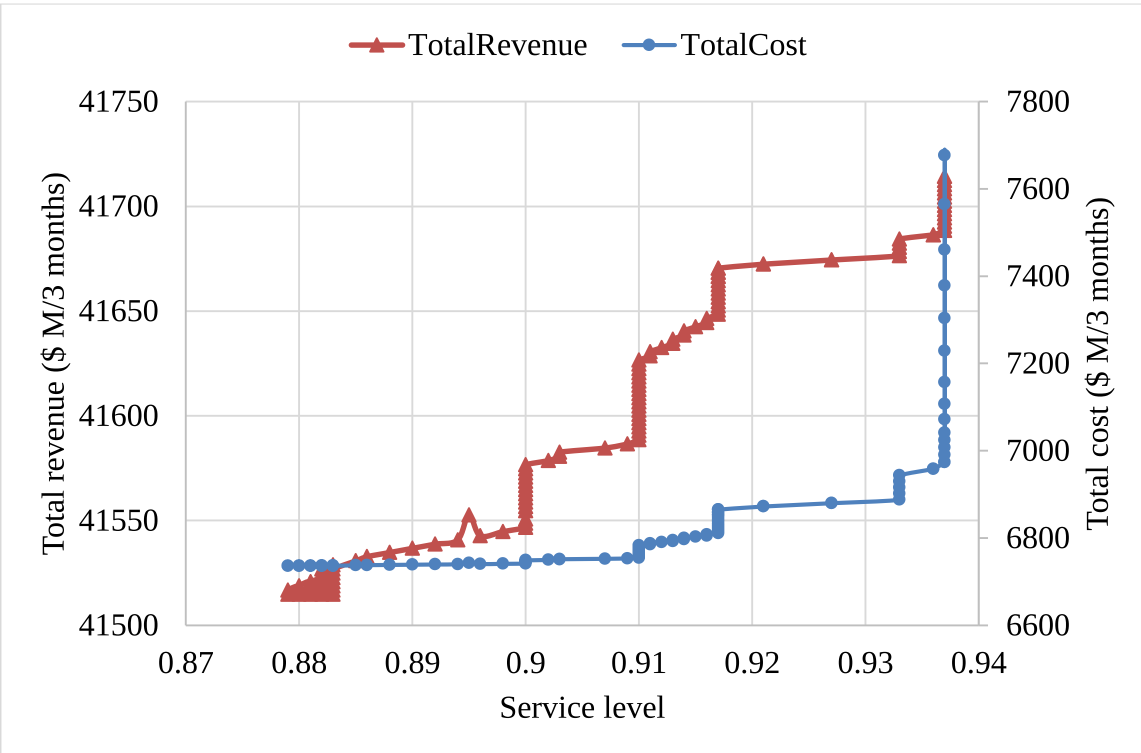


Figure 3.7 Variation of total revenue and total cost versus service level

Table 3.4 Service level of oil and gas at the three time periods.

Total cost ($ M/3 months)	Total revenue ($ M/3 months)	Service level	Oil service level			Gas service level		
			1st period	2nd period	3rd period	1st period	2nd period	3rd period
6735.989	41514.803	0.879	0.999	0.982	0.879	0.912	0.893	0.879
6738.472	41534.756	0.885	0.999	0.982	0.885	0.914	0.904	0.885
6743.461	**41554.708**	**0.900**	0.999	0.982	0.900	**0.919**	**0.904**	0.900
6748.449	**41574.661**	**0.900**	0.999	0.982	0.900	**0.928**	**0.916**	0.900
6758.746	41594.614	0.910	0.999	0.982	0.910	0.923	0.927	0.91
6773.957	41614.567	0.910	0.999	0.983	0.910	0.923	0.927	0.91
6792.511	41634.519	0.913	0.999	0.983	0.913	0.930	0.931	0.913
6824.164	41654.472	0.917	0.999	0.983	0.917	0.944	0.935	0.917
6879.881	41674.425	0.927	0.999	0.983	0.927	0.946	0.936	0.927
7024.024	41694.378	0.937	0.999	0.984	0.937	0.947	0.937	0.962

The trends of both oil processing and gas separation with respect to the service level are represented in Fig. 3.8. In general, as oil and gas volumes increase, service level increases. This can be explained as follows: As production volume increases, it means more sales which lead to higher service levels. As shown in Fig. 3.8, same service level values are obtained for different values of oil and gas volumes. This fact is exhibited again from Table 3.4.

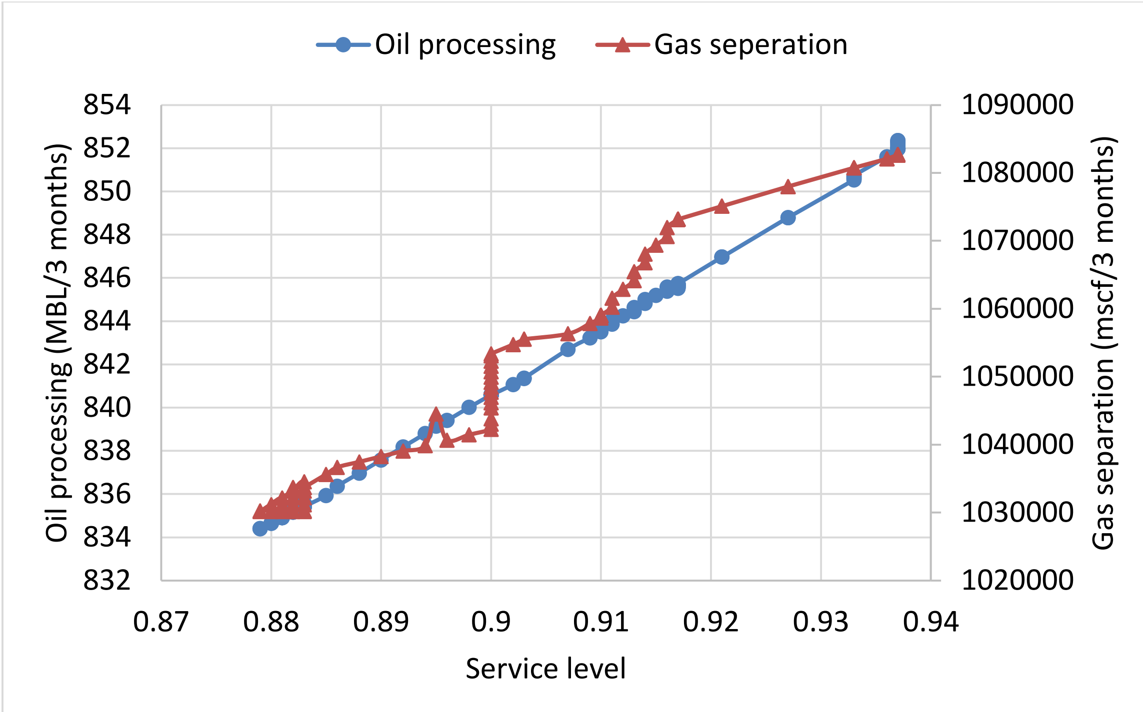


Figure 3.8 Service level versus oil and gas processing

The variation of crude oil cost elements (processing, transportation, holding, and penalty costs of above and below processing) with crude oil processing is illustrated in Fig. 3.9. As crude oil processing increases, processing costs, transportation costs, holding costs, and penalty cost of above processing increase, while the penalty cost of below processing is very low. The low penalty of the below-production cost is due to satisfying all demand of crude oil from local processing. This means that Kingdom of Saudi Arabia has sufficient resources and reserves to satisfy demands.

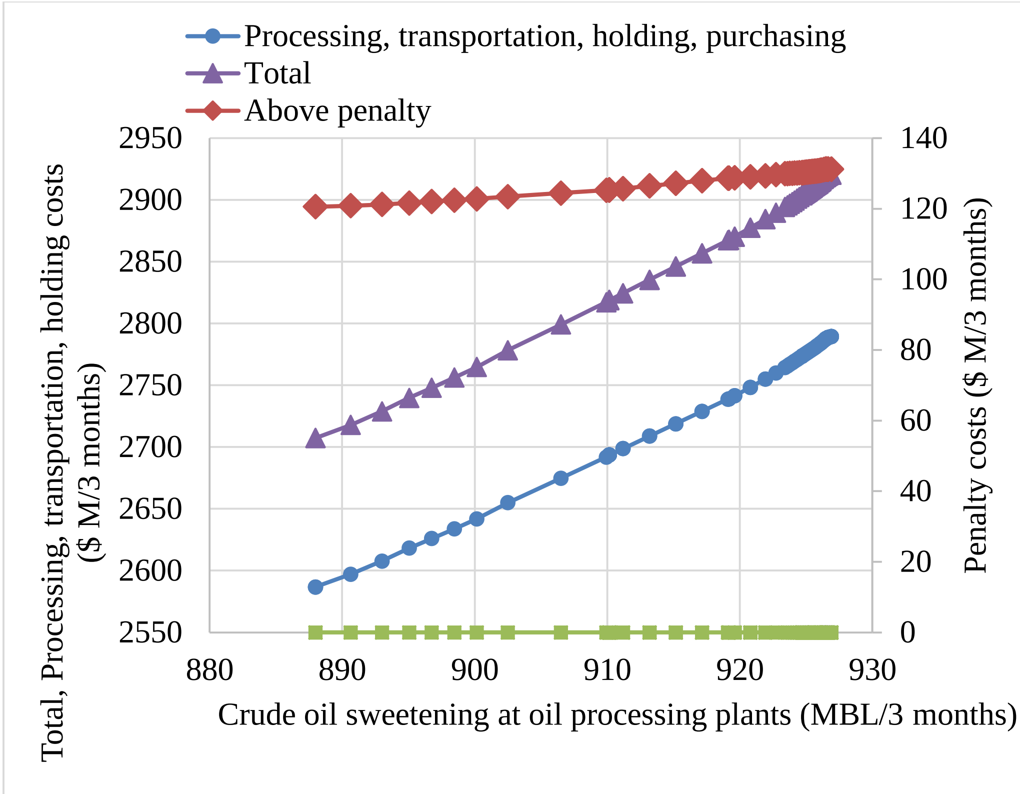


Figure 3.9 Cost elements variation with crude oil processing/processing

The trends of both gasoline and diesel imports with oil refined products refining from local refinery plants are illustrated in Fig. 3.10. It is obvious that as local oil refining quantities increase, the gasoline and diesel imports decrease since most of the demand is satisfied from local refining.

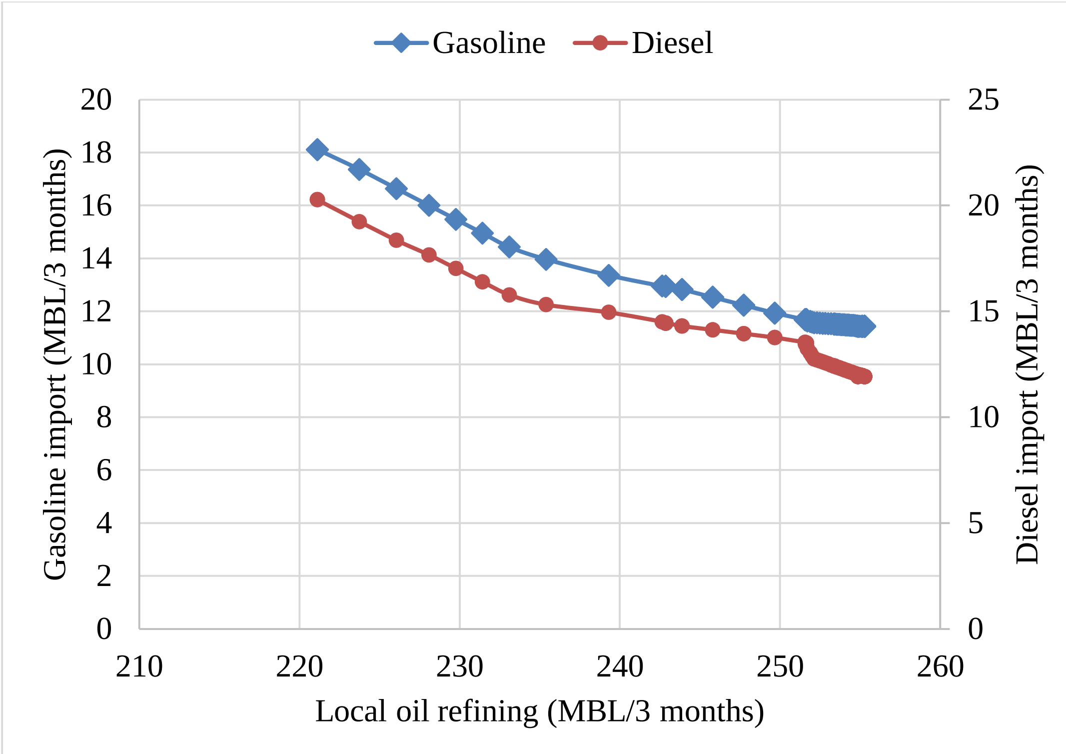
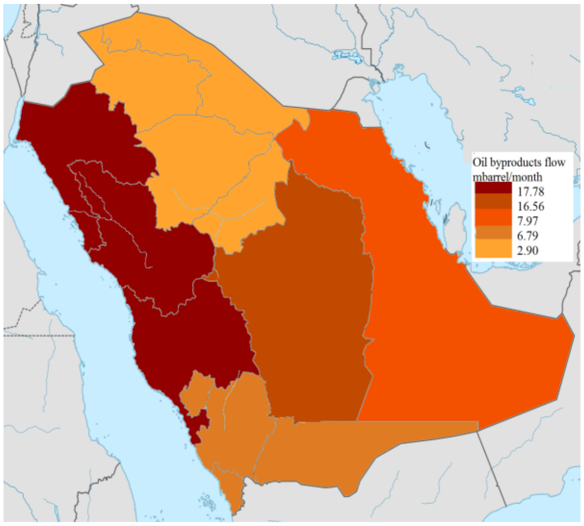


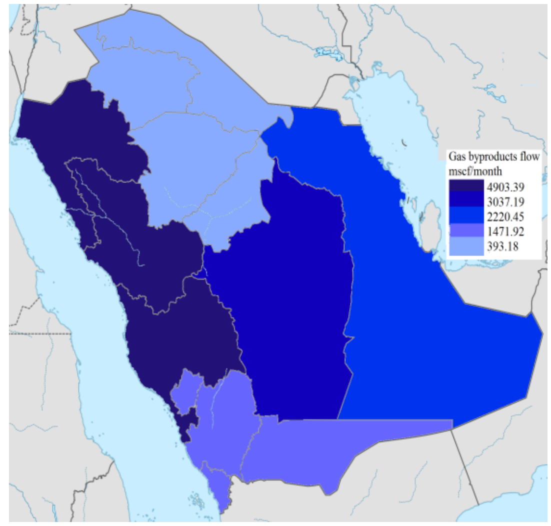
Figure 3.10 Gasoline and diesel imports versus local refining of oil refined products

For the purpose of comparison and explaining the tactical decisions behavior, the preferred tactical plan was chosen using TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) based on assigning equally weight to the three objectives. TOPSIS technique selects the nearest plan to the ideal one, (Clemen and Reilly, 2004).

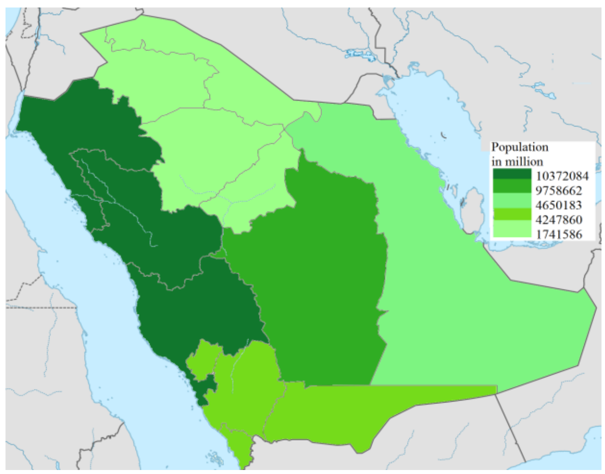
The distributions of oil refined products and gas products to the five regions of Kingdom of Saudi Arabia are presented in Fig. 3.9 (a) and (b), respectively. The flow of petroleum products is consistent with the population distribution shown in Fig. 3.11 (c).



(a) Distribution of oil refined products



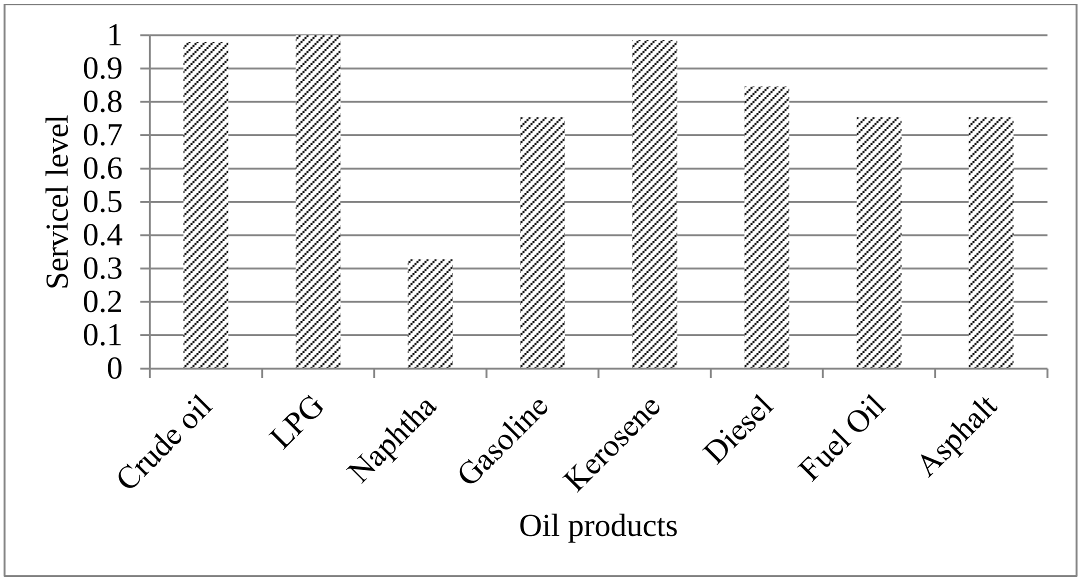
(b) Distribution of gas products



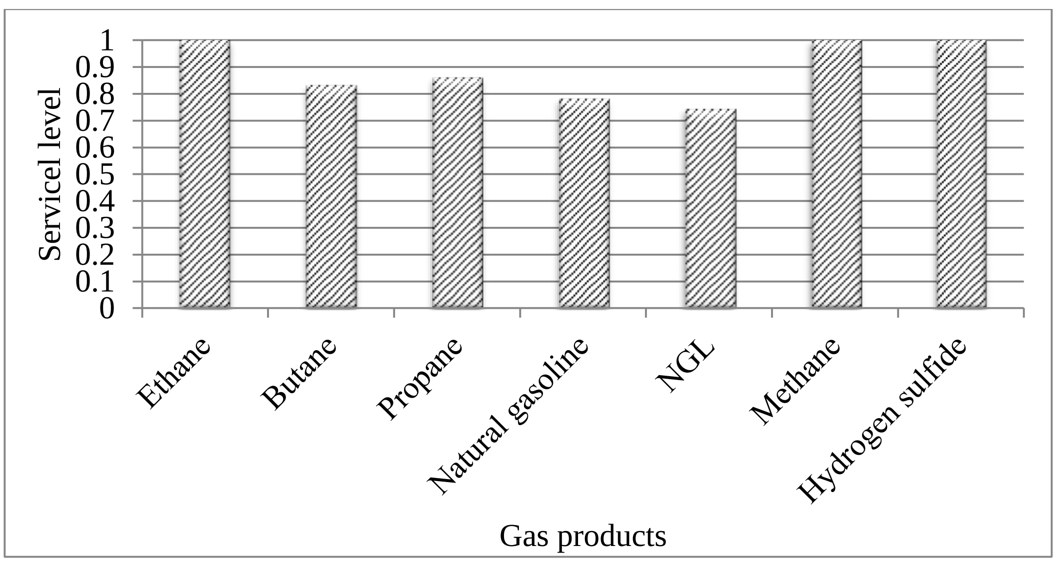
(c) Population density distribution

Figure 3.11 Distributions of oil and gas products to distinct regions of the Kingdom of Saudi Arabia and the population density of the Kingdom of Saudi Arabia.

Fig. 3.12 shows the service level of all considered petroleum products in this dissertation. Kingdom of Saudi Arabia can satisfy most of petroleum products with high values of service level. Some products show low service level values. For example, naphtha is satisfied with a percentage of 30% because the naphtha proportion in the crude oil is very small and the Kingdom of Saudi Arabia cannot fully operate its refinery plants to satisfy the naphtha needs since there is a high penalty costs for above productions of the other products in addition to the holding costs.



(a) Service levels of oil products



(b) Service levels of gas products

Figure 3.12 Service levels of all considered petroleum products

Utilization profile for refinery plants is depicted in Fig. 3.13. Most of refinery plants are fully utilized and some others are low utilized. For example, utilization of SASREF refinery plant is very low (57.9%), because the SASREF refinery plant is connected to only

Aljawf bulk plant which is used for satisfying part of local demand of the north region. The Rastunura refinery plant records a utilization of (87%) because it has huge capacity compared to other refinery plants.

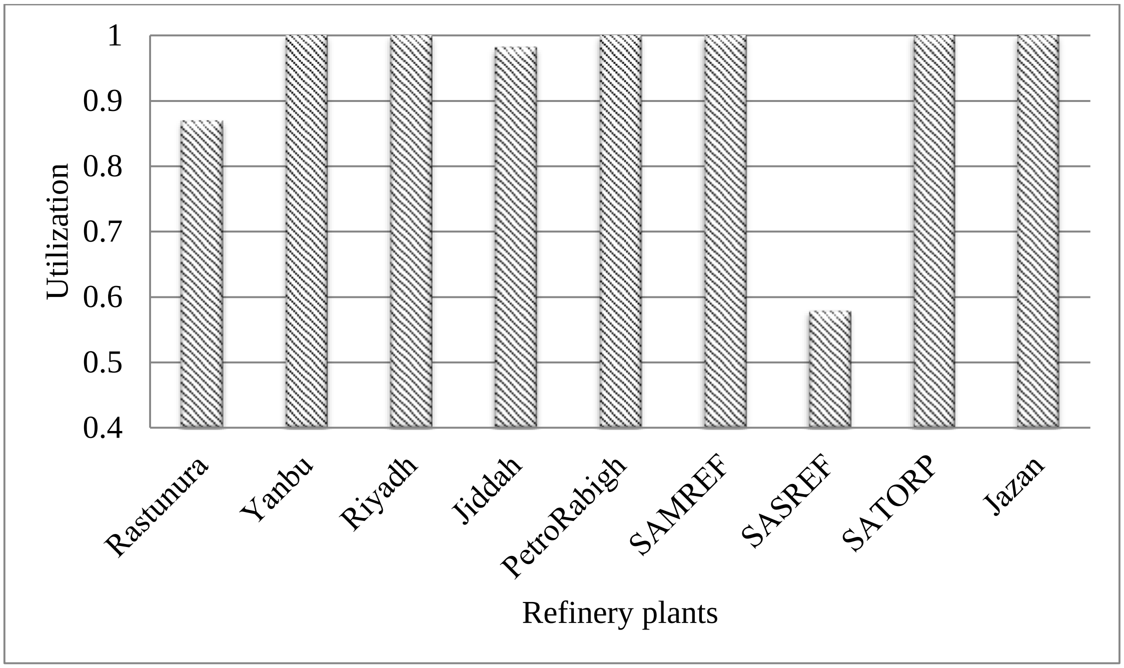


Figure 3.13 Utilization of refinery plants

To demonstrate the utility of the model, the model is solved under planning horizon of 6 months. Fig.3.14 clarifies the relationship between total cost and total revenue. If the decision maker selects the plan that gives high total revenue, he will face an increase in the total cost. On the other hand, if the plan with low total cost is selected, it means low total revenue will be obtained.

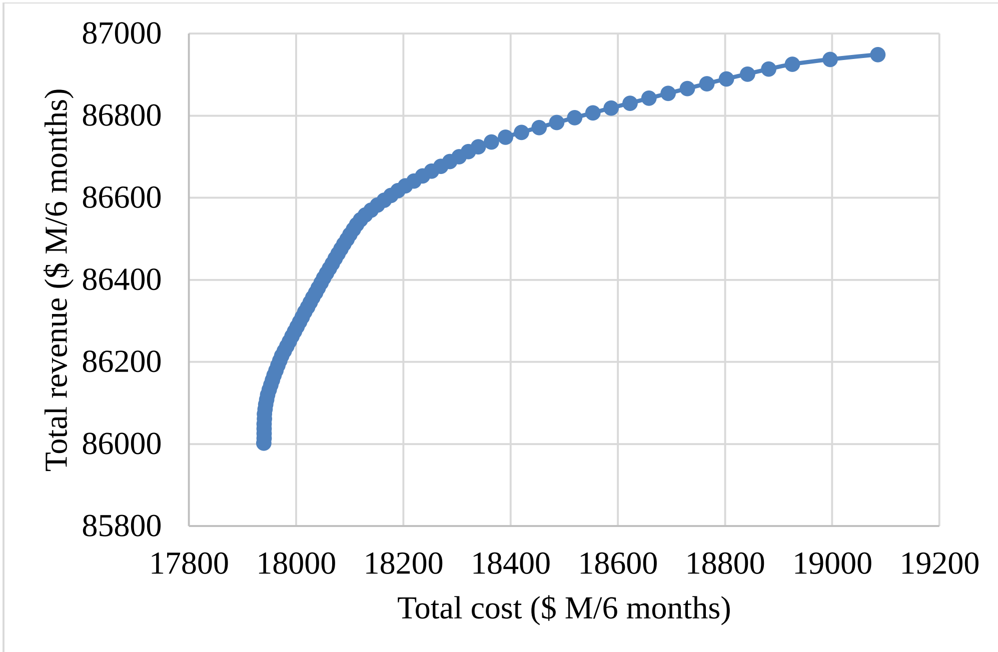
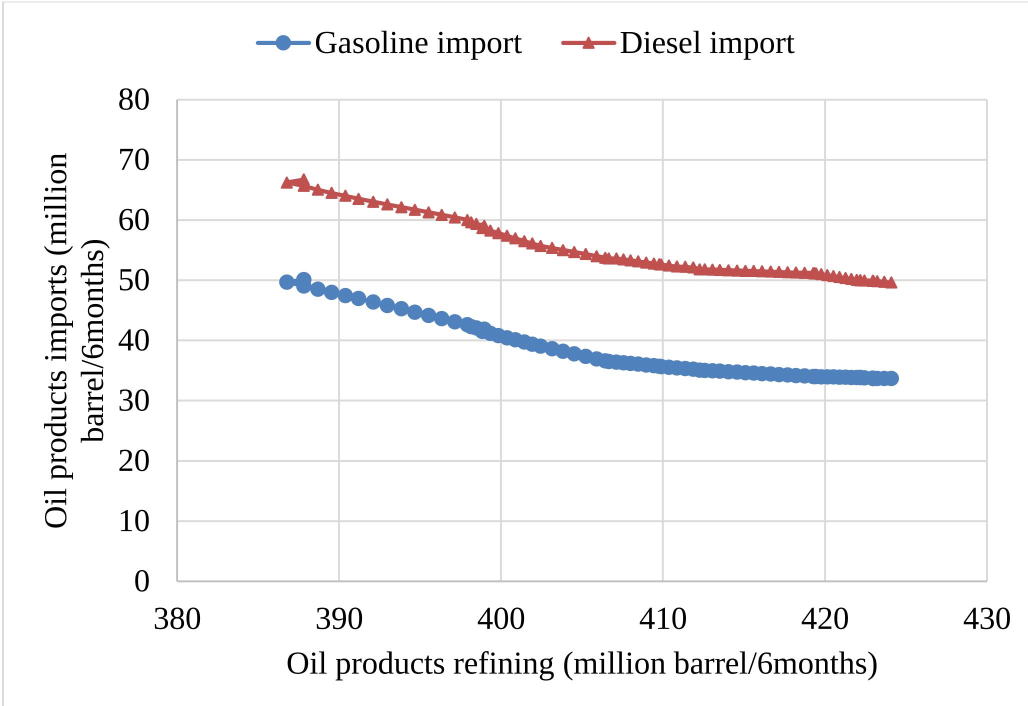
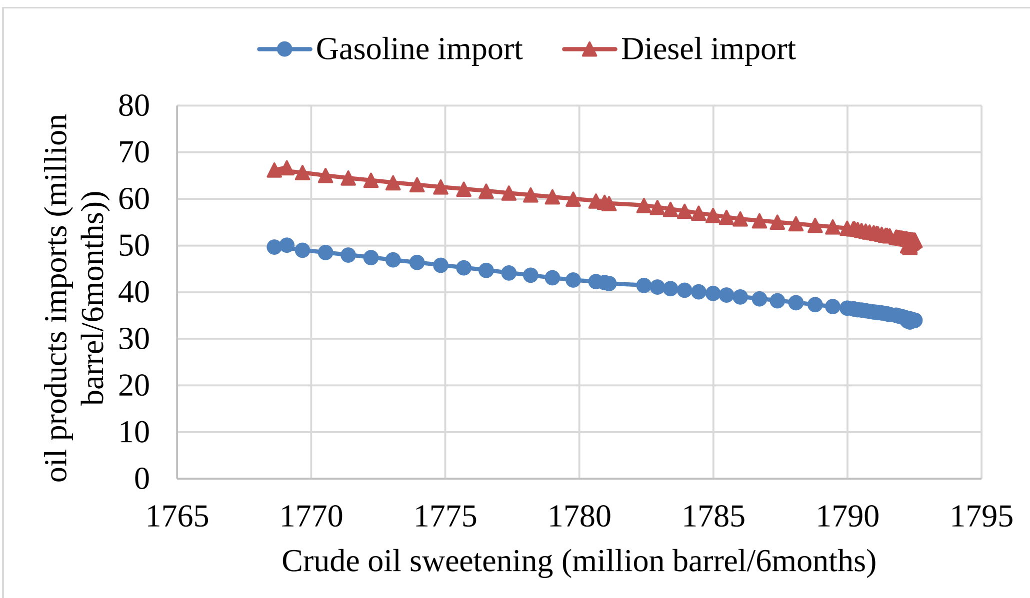


Figure 3.14 Pareto curve between total cost and total revenue with a planning horizon of 6 months

The variations of both gasoline and diesel imports with both oil refined products refining from local refinery plants and crude oil processing at oil processing plants are illustrated in Fig 3.15 (a) and (b), respectively.



a) Gasoline and diesel imports versus oil refined products refining



b) Gasoline and diesel imports versus crude oil processing

Figure 3.15 Oil imports versus oil refined products refining and crude oil processing

3.4.2 Sensitivity Analysis of MOD Model

In this section, sensitivity analysis for the MOD model's key parameters either controlled (OPEC quota) or uncontrolled (prices at international markets, and domestic demand) is conducted to assess their effects on the Pareto optimal solutions and to investigate the robustness of the model against the changes and variations in theses parameters.

These parameters are selected in the direction of detecting the ongoing negotiations between the OPEC members to overcome the sharp reduction in the prices of petroleum products. The OPEC members try to reduce the OPEC quota for each country. (Khan 2016) investigated and analyzed the causes and factors that lead to this reduction. He discussed two arguments regarding the reasons of oil price reduction; domestic oil boom in the United States and Iraq and the lack of agreement between OPEC members to reduce production despite the steady increase in non-OPEC oil production. Also it has been noticed a huge increase in the domestic demand of both oil and natural gas products in Kingdom of Saudi Arabia. Therefore, the sensitivity analysis helps in assessing the effect of the above mentioned parameters on valuable performance measures such as total revenue, total cost, and plants utilization.

The MOD model is run for several values of the OPEC quota (6 MBL/day– 11 MBL/day). The effect of OPEC quota on total revenue, total cost, and average utilization of oil processing plants are studied. The trends of both total revenue and total cost with OPEC quota are illustrated in Fig. 3.16. Decreasing OPEC quota from 11 MBL/day to 8 MBL/day, total revenue and total cost remain constant since the OPEC quota of 8 MBL/day has already satisfied the demand and also there is a limitation on the capacity of international terminals.

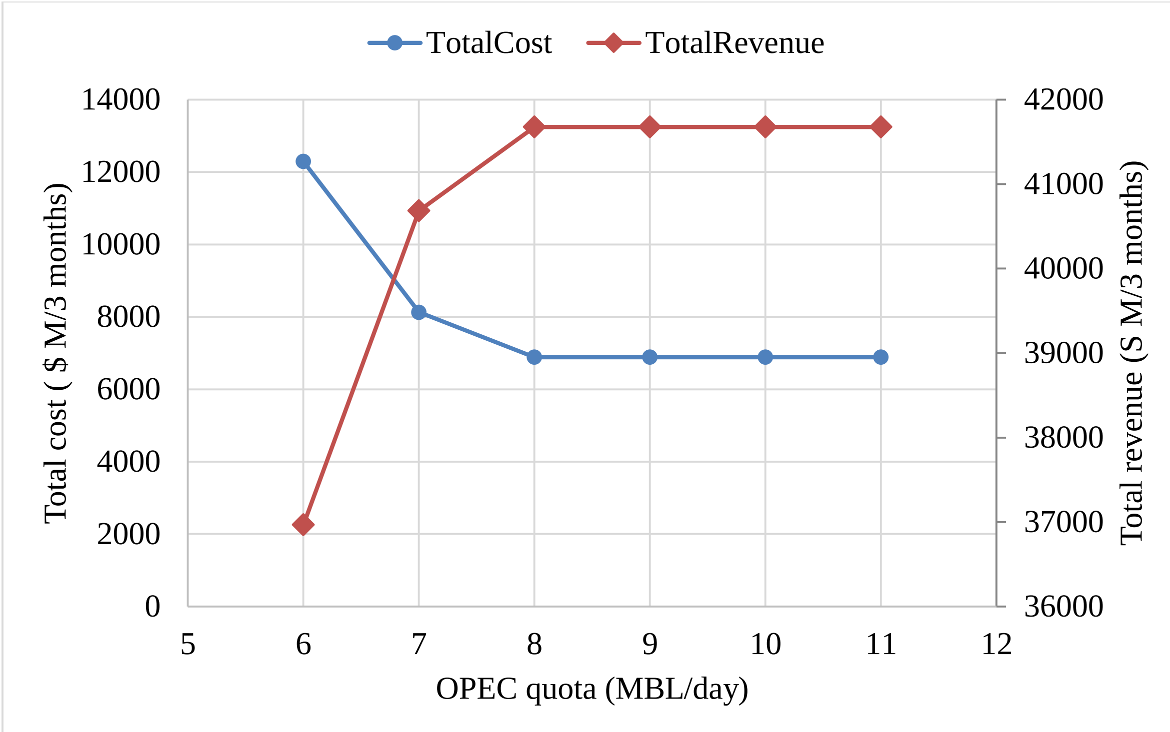


Figure 3.16 The effect of OPEC quota on both total revenue and total cost

Reducing OPEC quota more, e.g., from 8 MBL/day to 6 MBL/day, total revenue decreases sharply from almost $ 41676.4 M/3 months to $ 36967 M/3 months. On the other hand, as OPEC quota decreases from 8 MBL/day to 6 MBL/day, total cost increases from $ 6887.7 M/months up to $ 12290.9 M/3 months. The increases in total cost can be explained as follows: the crude oil exportation is limited by the OPEC quota. Therefore, as OPEC quota decreases, the local production cannot satisfy the demand due to the OPEC quota constraint. As a result, the demand is satisfied from the international market which leads to high under production cost that increases the total cost as shown in Fig. 3.17.

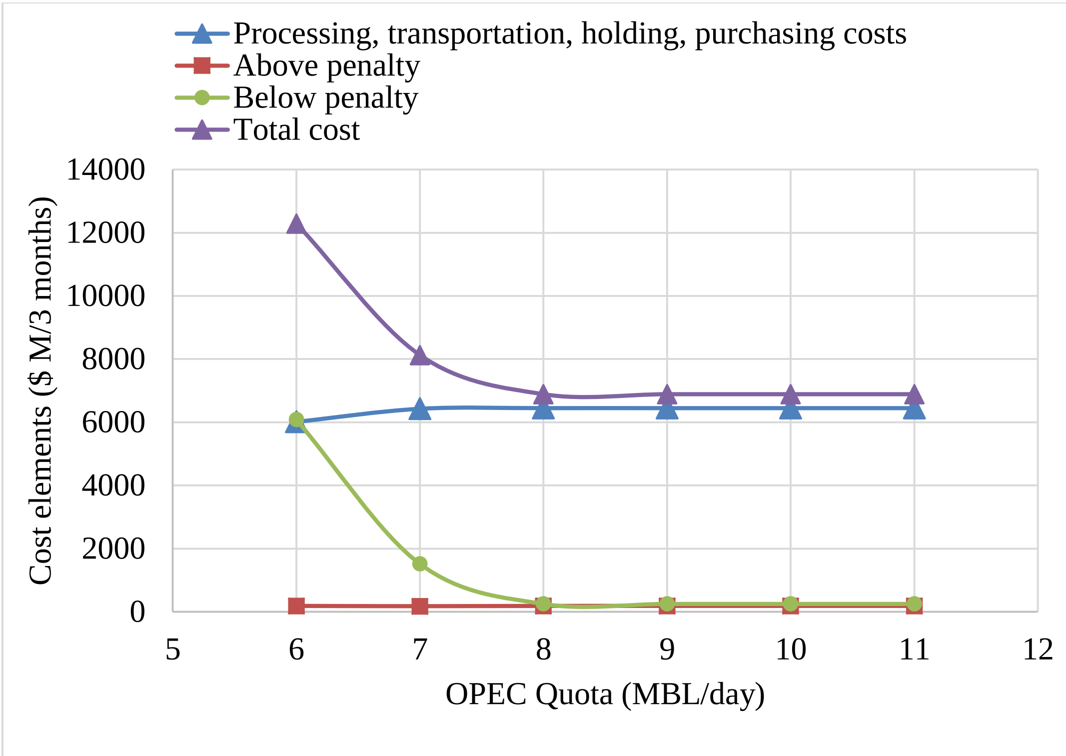


Figure 3.17 The effect of OPEC quota on cost elements

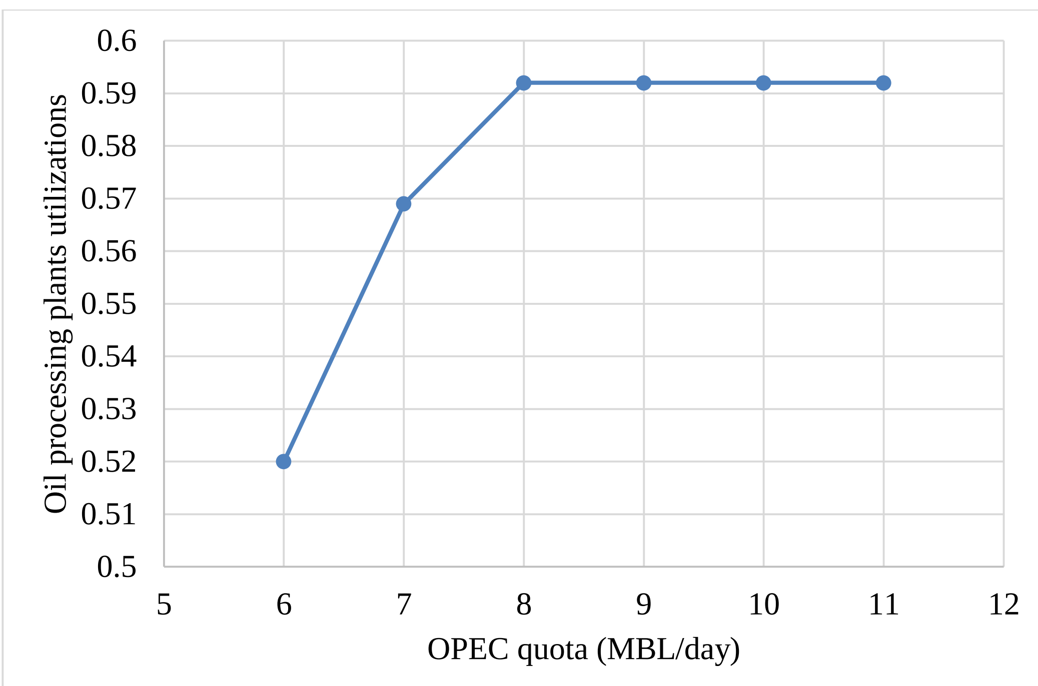


Figure 3.18 The effect of OPEC quota on the utilization of oil processing plants

Fig. 3.18 shows the effect of OPEC quota on average utilization of oil processing plants. The average utilization increases as OPEC quota increases. However, when increasing the OPEC quota to more than 8 MBL/day, the utilization remains constant. This constant relation occurs due to the fact that the 8 MBL/day already satisfies the demand and there is no need for more processing.

Next, the effect of increasing and decreasing the international prices of petroleum products is conducted on total revenue. As shown in Fig. 3.19, as price increases, total revenue increases in a linear fashion.

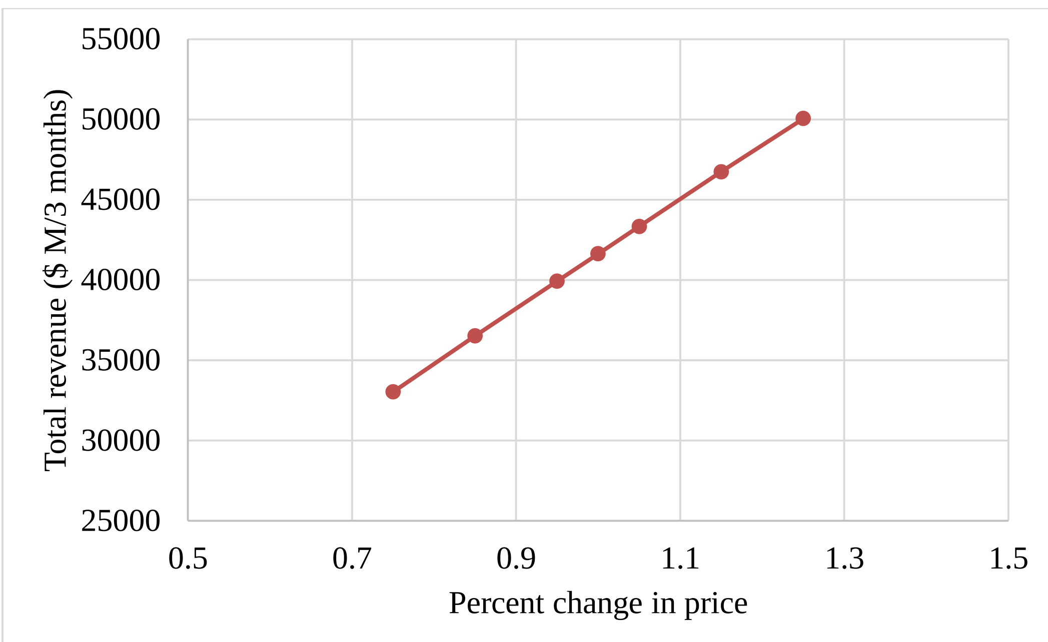


Figure 3.19 The effect of change in international prices on the total cost and revenue

In fact, as oil production or OPEC quota increases, oil offers in the markets increase which lead to low prices. This fact is investigated in Fig. 3.20 by varying OPEC quota and prices simultaneously to study their effect on total revenue. The figure shows that, if the OPEC quota is reduced to 7 million barrel/day and at the same time the prices increase 25 % to

50 % above the current prices, the Kingdom of Saudi Arabia will get high total revenue about $ 49000 million/3 months to $ 58000 $ million/3 months, respectively which is better than increasing OPEC Quota (for example to 9 million barrel /day) and decreasing the prices. If the above plan is followed, it will lead to high total revenue with low productions which is better to keep oil reserves for the coming generations.

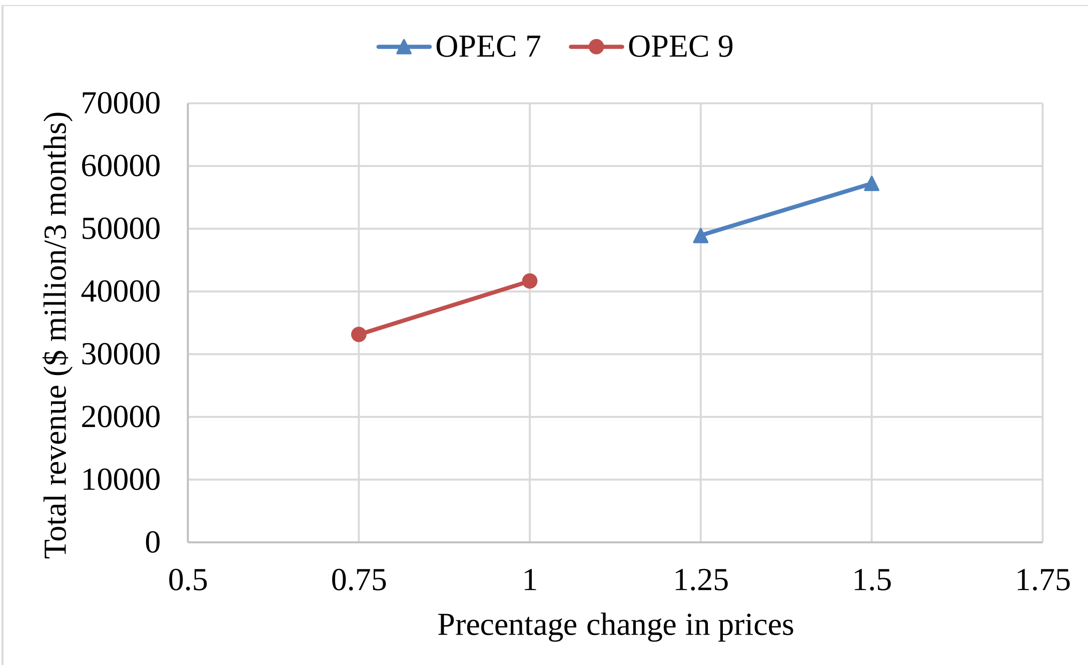


Figure 3.20 Effect of changing price and OPEC quota simultaneously on total revenue

Finally, the effect of changing domestic demand of both oil and gas products is conducted on average utilization of local refinery plants, total revenue, total cost, and import volumes. Fig. 3.21 shows refinery plants utilizations versus change in domestic demand. As domestic demand increases, local refining of crude oil increases which leads to more utilization of local refinery plants.

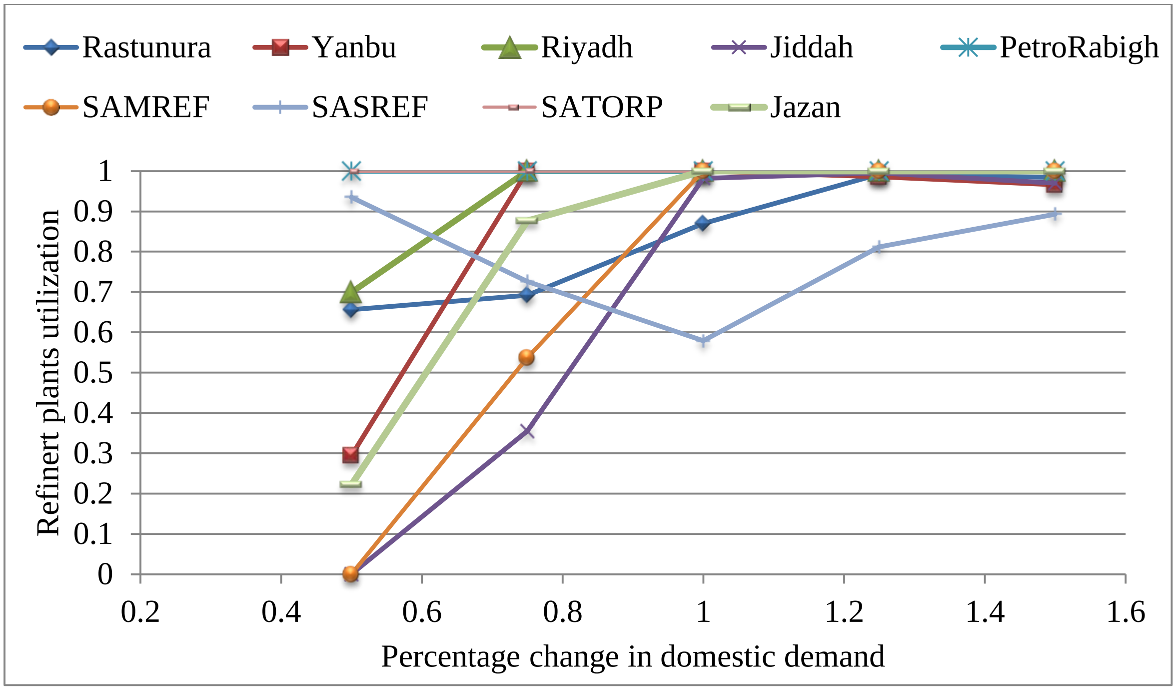


Figure 3.21 The effect of change in domestic demand on average utilization of refinery plants

Fig. 3.22 shows the change of gasoline and diesel imports with changing domestic demand of oil and gas products. As demand increases, both gasoline and diesel imports increase to meet the dramatic increase in the demand. Saudi Arabia cannot fully utilize its local refinery plants in order to satisfy the increase in demand of gasoline and diesel because high penalty incurred for producing other products more than the demand. Also, as demand increases, more local refining is needed.

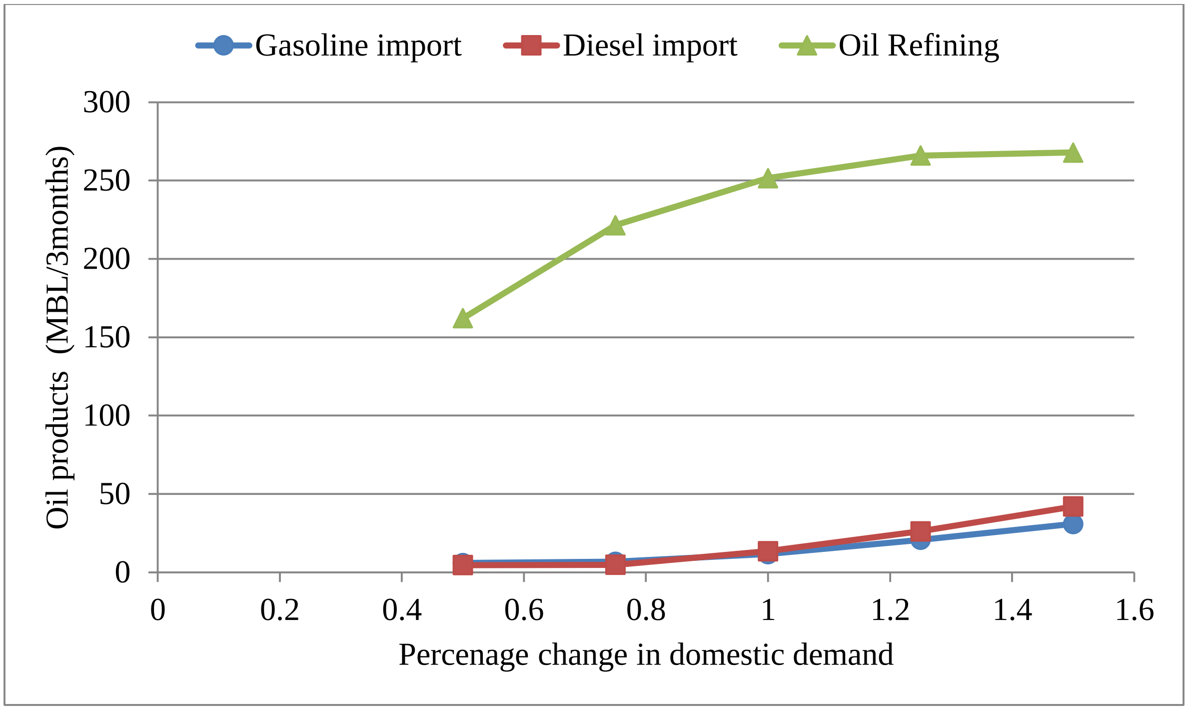


Figure 3.22 The effect of domestic demand on local oil refining and oil imports

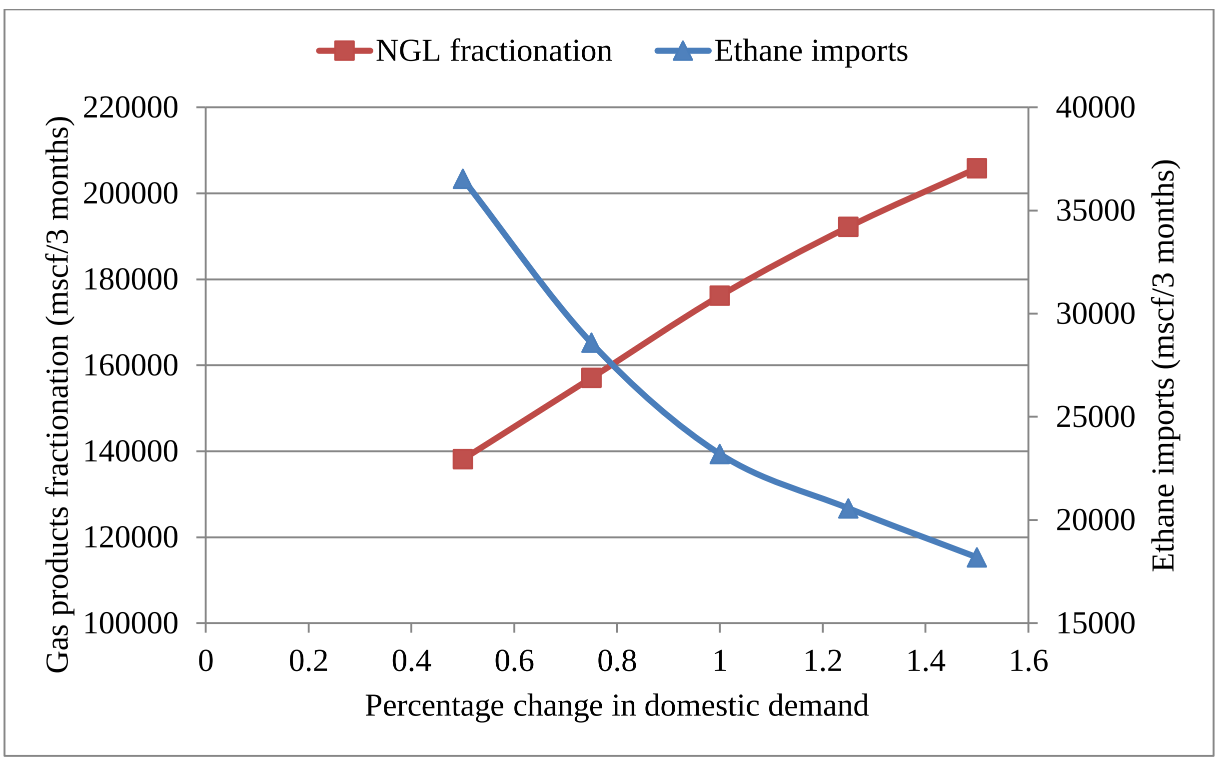


Figure 3.23 The effect of domestic demand on local gas fractioning and ethane import

The behavior of gas fractionating at fractionation plants and ethane import with changing domestic demand of oil and gas products are shown in Fig. 3.23. As demand increases, local gas fractionating increases to meet the increase in the demand. On the other hand, the ethane imports to satisfy the industry demand decreases. The ethane is used only for industry uses and the industry demand is assumed to be fixed. Therefore, increasing the domestic demands leads to more local fractioning of ethane and other gas products at fractionation plants. Therefore, the industry demand of ethane can be satisfied from the local fractioning then ethane import is reduced. In the actual case of Saudi Arabia, the local prices of petroleum products are low compared to other countries while the local demands are high. Conversely, if Saudi Arabia increases the local prices, local demands will decrease. To study this phenomena, the effect of changing local prices and local demand on cash flow is shown in Fig. 3.24. The results revealed that to get high cash flow, it is better to increase the local prices and thus decrease the domestic demand.

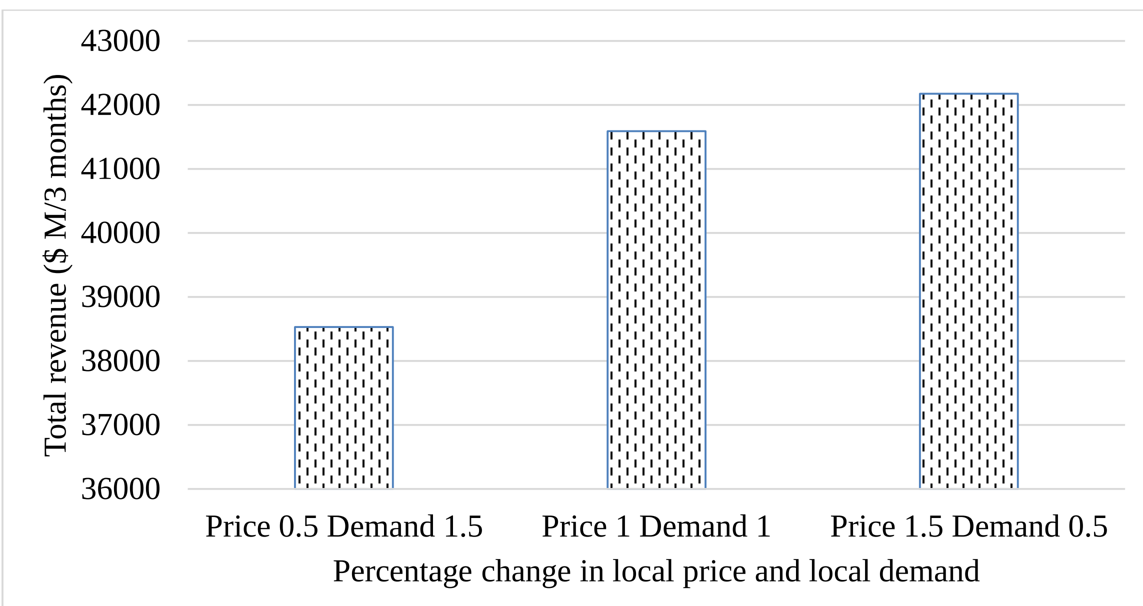


Figure 3.24 The effect of changing local price and local demand on cash flow

3.5 Conclusion

In this chapter, a multi-objective deterministic (MOD) optimization model for downstream oil and gas supply chain is developed under the assumption of fixed model parameters. Practical constraints such as mass balance, demand, capacities, service level and OPEC quota are considered. The trade-off between economic goals (total cost and total revenue) and customer service level have been investigated. The proposed MOD model helps in assessing the trade-off among different objectives for the Saudi Arabia downstream HCSC and guides the decision maker to choose the preferred tactical plans among the Pareto optimal solutions. The model allows quantifying the petroleum processing volumes and investigates their impact on oil and gas imports, resources utilizations, total revenue and cost elements. It is noted that using this multi-dimensional and multi-objective model has considerable impact on all the tactical decisions. The MOD model was evaluated and analyzed by conducting sensitivity analysis to study the effect of controlled and uncontrolled parameters on performance measures.

The sensitivity analysis is very useful especially in the current situations, since there is an ongoing argument among the OPEC countries to reduce the oil production in order to overcome the huge reduction in petroleum products prices. The MOD model shows that if the oil production or OPEC quota decreases and at the same time the prices increase, the return will be higher than in the current situation. Related to domestic demand, the results revealed that to get high revenue, it is better to increase the local prices and decrease the domestic demand. It is noted that Kingdom of Saudi Arabia has the ability of satisfying the demand for most of the petroleum products with a high value of service level since Kingdom of Saudi Arabia has sufficient resources and reserves.

Using the TOPSIS technique the best plan is to process oil at a rate of 10.27 MBL/day to satisfy both domestic and international demands. For gas, the preferred processing level at gas plants is 11870 Mcft/day. To satisfy oil refined products demands, the Kingdom of Saudi Arabia should refine 2.82 MB/day and import 0.28 MBL/day of gasoline and diesel. The selected plan costs the Kingdom $ 6888 M/3 months and generates a cash flow of $ 41676 M/3 months with a 0.933 service level.

To dispense oil and gas imports, Kingdom of Saudi Arabia has to increase oil refining to 2.90 MBL/day instead of 2.82 MBL/day in the current case, and gas fractionation to 1999 Mcft/day instead of 1957 Mcft/day in the current case. Although the advantages of the proposed MOD model, it has some limitations such as: (1) not addressing the nonlinearity of the refinery operations, (2) linearity of transportation cost where transportation cost has a nonlinear relation with transported quantity, (3) considering all the transportation done using pipelines which is correct only for Saudi Arabia, and (4) disregarding the uncertainty in market behavior in formulation. In addition to the nature of multi-objective optimization which does not provide the decision maker with a one solution. Some of these limitations are addressed in the next chapters.

CHAPTER 4

MULTI-OBJECTIVE STOCHASTIC MODEL

4.1 Introduction

Life is full of uncertainty and this fact is increasing in petroleum industries. Uncertainty in HCSC arises because of variation in uncontrolled parameters including demand, supply, and prices, etc. For instant, the lack of understanding of population growth and expanding of industrial and petrochemical plants leads to variation of petroleum products demand. Due to political issues, inventing of renewable and nuclear energies, and high productions, big variation in the prices of petroleum products have been recorded. Therefore, the petroleum producing countries have to build their production and marketing plans in a multi-dimensional framework and under uncertainty. The uncertain parameters of the petroleum industry and markets are the driving forces for improvements in the oil and gas production and marketing planning processes.

In this chapter, the MOD model formulated in chapter three is extended to consider the effect of uncertainty in market conditions. The proposed and obtained model is Multi-Objective Stochastic (MOS) model. Uncertainties were incorporated to the proposed model considering the variations of petroleum products demands and prices. The MOS model was formulated based on the two-stage program with fixed recourse approach with the assumption of finite number of realizations of the uncertain parameters. From the literature, the two-stage stochastic model is the most commonly used in planning of supply chain under uncertainty.

The main purpose of this chapter is to study the impact of uncontrolled parameters; price and demand on the tactical decisions of the integrated downstream oil and gas supply chain. The tactical decisions related to downstream activities including: crude oil and natural gas processing, oil and gas separation and transforming volumes, flows of crude oil, oil refined products, and gas products between each two nodes of the supply chain, imports and exports volumes, and inventory levels. The model helps in assessing various trade-off among different objectives and guides decision makers for effective management of the downstream HCSC under uncertainty in demand and price.

The rest of this chapter is organized as follows: section 4.2 presents the concept of modeling under uncertainty focusing on the two-stage stochastic programming approach followed by the MOS model formulation in section 4.3. The utility of the proposed model is demonstrated using a Saudi Arabia HCCS case and the effect of uncertainty is tested and compared with the deterministic model in section 4.4. Also, section 4.4 presents sensitivity analysis in order to study the effect of different scenarios of prices and demands. Finally, the chapter is concluded in section 4.5.

4.2 Modeling under Uncertainty

Downstream HCSC comprises uncertain parameters such as prices, demand, yields, etc. Accordingly, during modeling of HCSC it is important to take into account these uncertainties. The stochastic programming approach is one of the most suitable approaches for modeling problem involves uncertainties. Therefore, in this section the two-stage stochastic programming is focused on and used in this dissertation.

The two-stage stochastic formulation is a decision making approach in which decisions are performed sequentially at two stages. Where the first stage decisions *x* (here-and–now) decisions are made before having clear information about the uncertain parameters λ(ω). After the recognition of the uncertain parameter λ, the second stage decisions *y* (wait-and-see) decisions are made. A recourse action is taken during the second stage after the uncertainty is cleared. The stochastic linear programming formulation for the two-stage problem in terms of a single objective is shown below, in Eqs. (4.1-4.6) and the deterministic equivalent for it is provided in Eqs. (4.7-4.10), Conejo et al (2010).

$$Maximize_x \; z = c^T x + E\{Q(\omega)\} \qquad 4.1$$

$$subject\ to\ Ax = b \qquad 4.2$$

$$x \in X \qquad 4.3$$

where

$$Q(\omega) = \{Maximize_{y(\omega)} q(\omega)^T y(\omega) \qquad 4.4$$

$$subject\ to\ T(\omega)x + W(\omega)y(\omega) = h(\omega) \qquad 4.5$$

$$y(\omega) \in Y\}, \qquad \forall \omega \in \Omega \qquad 4.6$$

The deterministic equivalent model of the above formulation is shown below:

$$Maximize_{x,y(\omega)} \; z = c^T x + \sum_{\omega \in \Omega} \pi(\omega) q(\omega)^T y(\omega) \qquad 4.7$$

$$subject\ to\ Ax = b \qquad 4.8$$

$$T(\omega)x + W(\omega)y(\omega) = h(\omega), \qquad \forall \omega \in \Omega \qquad 4.9$$

$$x \in X, y(\omega) \in Y, \qquad \forall \omega \in \Omega \qquad 4.10$$

Where $\pi(\omega)$ is the probability of occurrence of uncertain parameters. In terms of the multi-objective case, the two stage stochastic model is represented mathematically as follows:

$$Maximize\, f1 = C_1^T x + \sum_{\omega \in \Omega} \pi(\omega) q_1(\omega)^T y(\omega) \qquad 4.11$$

$$Maximize f2 = C_2^T x + \sum_{\omega \in \Omega} \pi(\omega) q_2(\omega)^T y(\omega) \qquad 4.12$$

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$$Maximize\, fn = C_n^T x + \sum_{\omega \in \Omega} \pi(\omega) q_n(\omega)^T y(\omega) \qquad 4.13$$

$$subject\ to\ \ Ax = b \qquad 4.14$$

$$T(\omega)x + W(\omega)y(\omega) = h(\omega), \qquad \forall \omega \in \Omega \qquad 4.15$$

$$x \in X,\ y(\omega) \in Y, \qquad \forall \omega \in \Omega \qquad 4.16$$

The nature of the objective function, input parameters, decision variables, and constraints, in addition to the size of the problem, force the researcher to select and/or establish a suitable solution technique. In the two-stage stochastic modeling, if the number of scenarios that represent the uncertain parameters is small, the stochastic linear programming is formulated by scenario based approach and can be solved directly using a commercial programming solver. However, if the number of scenarios is very high, it is necessary to use solution methods that are designed to exploit the structural of the stochastic program such as L-shaped decomposition approach and sample average approximation (SAA) methods. When the computational time of solving the stochastic problem is very high, heuristic algorithms can be applied. In this dissertation, a two-stage stochastic scenario based is used as a formulation approach. The resulted multi-objective stochastic model was converted into a multi-objective deterministic equivalent model. The deterministic equivalent model is coded in a commercial solver and then solved using an improved version of ε-constraint method.

4.3 MOS Model Formulation

In this section, the formulated MOD model described in section 3.2 is extended to handle the uncertainty in demand and price. Each uncertain parameter is represented by discrete possible realization/scenarios with a specific probability of occurrence. The MOS model is formulated based on two-stage stochastic programming approach with fixed recourse (Dantzig, 1955), also known as scenario based analysis (Birge and Louveaux, 1997).

The first-stage decisions (here-and-now) corresponds to the supply and processing variables at the first echelon (oil processing plants and gas plants). Due to the lead times involved in the oil and gas processing, the processing decisions are made prior to the realization of demand and price. Also, due to the location of the uncertain parameters in the network, the first and second stage decisions are selected. The second-stage decisions (wait-and-see) comprises quantities of all shipments between each two nodes in the network, transforming and separation, inventory levels, as well as importation and exportation quantities. The notations of sets, subsets, decision variables, and parameters used in this section are defined below.

4.3.1 MOS Model Notations

Table 4.1 Notations of the MOS model

Sets	
$i\,,j\ \in I$	All nodes
h	Set of well head stream oil
N	Set of natural gases
C	Set of crude oil types
O	Set of oil refined products
G	Set of gas products
T	Set of time periods
Ω	Set of scenarios
Subsets	
$s, r, b \subseteq I$	Oil processing plants, refinery plants, and bulk plants
$a, f\ \subseteq I$	Gas plants and fractionation plants.
$e,\ u,\ d \subseteq I$	Demand nodes: local regions, international terminals, and industries
$k \subseteq I$	Import nodes.
$h\ \in H$	Well head stream oil type h: Arabian light, Arabian extra light, Arabian medium, and Arabian heavy.
$c\ \in C$	Crude oil type c: Arabian light, Arabian extra light, Arabian medium, and Arabian heavy; after processing.
$o\ \in O$	Oil refined products: LPG, Naphtha, Gasoline, Diesel, Kerosene, Fuel oil, and Asphalt.
$n\ \in N$	Natural gas: associated and non-associated.
$g\ \in G$	Gas products: Natural gas liquid, Methane, Ethane, Propane, Butane, Natural gasoline, and Hydrogen sulfide.
$\omega\ \in \Omega$	Joint scenarios
Decision Variables	
Supply from upstream:	

X_{st}^{h}	Supply of well head stream type h from upstream to oil processing plant s, at time t.
Y_{at}^{n}	Supply of natural gas type n from upstream to gas plant a, at time t.
Production and processing quantity:	
X_{st}^{c}	Amount of crude oil c sweetened and processed at oil processing plant s at time period t.
Y_{at}^{g}	Amount of gas g processed at gas plant a at time period t.
$X_{r\omega t}^{o}$	Amount of oil refined products o refined at refinery plant r at time period t under scenario ω.
$Y_{f\omega t}^{g}$	Amount of gas products g fractionated at fractionation plant r at time period t under scenario ω.
Flow quantity:	
$X_{sr\omega t}^{c}$	Amount of crude oil c transported from oil processing plant s to refinery plant r at time period t under scenario ω .
$X_{su\omega t}^{c}$	Amount of crude oil c transported from oil processing plant s to international terminal u at time period t under scenario ω.
$X_{ru\omega t}^{o}$	Amount of oil refined products o transported from refinery plant r to terminal u at time period t under scenario ω.
$X_{rb\omega t}^{o}$	Amount of oil refined products o transported from refinery plant r to bulk plant b at time period t under scenario ω.
$X_{be\omega t}^{o}$	Amount of oil refined products o transported from bulk plant b to domestic region e at time period t under scenario ω.
$X_{bd\omega t}^{o}$	Amount of oil refined products o transported from bulk plant b to industry d at time period t under scenario ω.
$Y_{au\omega t}^{g}$	Amount of gas g transported from gas plant a to international terminal u at time period t under scenario ω.
$Y_{ad\omega t}^{g}$	Amount of gas g transported from gas plant a to industry d at time period t under scenario ω.
$Y_{af\omega t}^{g}$	Amount of gas g transported from gas plant a to fractionation plant f at time period t under scenario ω.
$Y_{fu\omega t}^{g}$	Amount of gas products g transported from fractionation plant f to terminal u at time period t under scenario ω.
$Y_{fd\omega t}^{g}$	Amount of gas products g transported from fractionation plant f to industry d at time period t under scenario ω.

$Y^{g}_{fe\omega t}$	Amount of gas products g transported from fractionation plant f to t region e at time period t under scenario ω.

Production above and below demand

$x^{c+}_{u\omega t}, x^{c-}_{u\omega t}$	Production of crude oil c above and below the demand of international market at terminal u during time period t under scenario ω.
$X^{o+}_{u\omega t}, X^{o-}_{u\omega t}$ $X^{o+}_{e\omega t}, X^{o-}_{e\omega t}$ $X^{o+}_{d\omega t}, X^{o-}_{d\omega t}$	Production of oil refined products o above and below the demand of terminal u, region e, and industry d at time t under scenario ω.
$Y^{g+}_{u\omega t}, Y^{g-}_{u\omega t}$ $Y^{g+}_{e\omega t}, Y^{g-}_{e\omega t}$ $Y^{g+}_{d\omega t}, Y^{g-}_{d\omega t}$	Production of gas products g above and below the demand of terminal u, region e, and industry d at time t under scenario ω.

Service levels

$SLO_{\omega t}$	Service level of oil products during time period t under scenario ω.
$SLG_{\omega t}$	Service level of gas products during time period t under scenario ω.
$MTSL$	A minimum target for the service level, which must be attained in all the time intervals t.

Parameters

Capacity

AC_{su}	Capacity of routes connecting oil processing plant s with international terminal u.
AC_{sr}	Capacity of routes connecting oil processing plant s with refinery plant r.
AC_{ru}	Capacity of routes connecting refinery plant r with international terminal u.
AC_{rb}	Capacity of routes connecting refinery plant r with and bulk plant b.
AC_{be}	Capacity of routes connecting bulk plant b with domestic region e.
AC_{bd}	Capacity of routes connecting bulk plant b with industry d.
AC_{af}	Capacity of routes connecting gas plant a with fractionation plant f.
AC_{ad}	Capacity of routes connecting gas plant a with industry d.

AC_{au}	Capacity of routes connecting gas plant a with international terminal u.
AC_{fu}	Capacity of routes connecting fractionation plant f with international terminal u.
AC_{fe}	Capacity of routes connecting fractionation plant f with domestic region e.
AC_{fd}	Capacity of routes connecting fractionation plant f with industry d.
CP_s	Capacity of oil processing plant s
CP_a	Capacity of gas plant a
CP_r	Capacity of refinery plant r
CP_f	Capacity of fractionation plant f
CP_u	Capacity of international terminal u
Demand	
$D^c_{u\omega t}$	Demand for crude oil type c at international terminal u at time t under scenario ω.
$D^o_{e\omega t}$	Demand for oil refined products o at region e at time t under scenario ω.
$D^o_{u\omega t}$	Demand for oil refined products o at terminal u at time t under scenario ω.
$D^o_{d\omega t}$	Demand for oil refined products o at industry d at time t under scenario ω.
$D^g_{e\omega t}$	Demand for gas products g at region e at time t under scenario ω.
$D^g_{u\omega t}$	Demand for gas products g at terminal u at time t under scenario ω.
$D^g_{d\omega t}$	Demand for gas products g at industry d at time t under scenario ω.
Costs Parameters:	
PC^h_{st}	Unit processing cost of well head stream h at oil processing plant s at time t.
PC^n_{at}	Unit processing cost of natural gas type n at gas plant a at time t.
SC^c_{srt}	Unit transformation cost of oil stream X^c_{srt} at refinery plant r at time t.
SC^g_{aft}	Unit separation cost of gas stream Y^g_{aft} at fractionation plant f at time t.
IC^o_{kt}	Unit purchasing cost of imported oil refined products o from import market k at time t.

IC_{kt}^{g} Unit purchasing cost of imported gas products g from import market k at time t.

CT_{srt}^{c} Unit transportation cost of f oil stream X_{srt}^{c} between oil processing plant s and refinery plant r at time t.

CT_{sut}^{c} Unit transportation cost of f oil stream X_{sut}^{c}between oil processing plant s and terminal u at time t.

CT_{rut}^{o} Unit transportation cost of oil refined products o between refinery plant r and terminal u at time t.

CT_{rbt}^{o} Unit transportation cost of oil refined products o between refinery plant r and bulk plant b at time t.

CT_{bet}^{o} Unit transportation cost of oil refined products o between bulk b and region e at time t.

CT_{bet}^{o} Unit transportation cost of oil refined products o between bulk b industry d at time t.

CT_{aut}^{g} Unit transportation cost of gas products g between gas plant a and terminal u at time t.

CT_{adt}^{g} Unit transportation cost of gas products g between gas plant a industry d at time t.

CT_{aft}^{g} Unit transportation cost of gas products g between gas plant a and fractionation plant f at time t.

CT_{fut}^{g} Unit transportation cost of gas products g between fractionation plant f and terminal u at time t.

CT_{fdt}^{g} Unit transportation cost of gas products g between fractionation plant f industry d at time t.

CT_{fet}^{g} Unit transportation cost of gas products g between fractionation plant f and region e at time t.

HC_{st}^{h} Inventory holding cost of well head h at oil processing plant s at time t.

HC_{at}^{n} Inventory holding cost of natural gas n at gas plant a at time t.

HC_{rt}^{c} Inventory holding cost of crude oil c at refinery plant r at time t.

HC_{bt}^{o} Inventory holding cost of oil refined products o bulk plant b at time t.

HC_{ft}^{g}	Inventory holding cost of gas products g at fractionation plant f at time t.
w_{ut}^{c+}, w_{ut}^{c-}	Penalty cost of producing crude oil c above, below the specified demand of terminal u at time t.
w_{ut}^{o+}, w_{ut}^{o-} w_{et}^{o+}, w_{et}^{o-} w_{dt}^{o+}, w_{dt}^{o-}	Penalty cost of producing oil refined products o above, below the specified demand of terminal u, region e, and industry d at time t.
w_{ut}^{g+}, w_{ut}^{g-} w_{et}^{g+}, w_{et}^{g-} w_{dt}^{g+}, w_{dt}^{g-}	Penalty cost of producing gas products g above, below the specified demand terminal u, region e, and industry d at time t.
Selling Prices Parameters:	
$SP_{u\omega t}^{c}$	Selling price of crude oil c at terminal u at time t under scenario ω.
$SP_{e\omega t}^{o}$	Selling price of oil refined products o at region e at time t under scenario ω.
$SP_{u\omega t}^{o}$	Selling price of oil refined products o at terminal u at time t under scenario ω.
$SP_{d\omega t}^{o}$	Selling price of oil refined products g at industry d at time t under scenario ω.
$SP_{e\omega t}^{g}$	Selling price of gas products g at region e at time t under scenario ω.
$SP_{u\omega t}^{g}$	Selling price of gas products g at terminal u at time t under scenario ω.
$SP_{d\omega t}^{g}$	Selling price of gas products g at industry d at time t under scenario ω.
Yields and OPEC Parameters:	
P_{st}^{hc}	Yields of crude oil obtained from input well head stream h to oil processing plant s at time t.
P_{at}^{ng}	Yields of gas products g obtained from input stream n to gas plant a at time t.
P_{srt}^{co}	Yields of oil refined products o obtained from input stream to refinery plant r at time t.
$OPEC_{t}$	OPEC quota or market share allocated to specific country at time t.
dr	Discount rate per period t.
π_{ω}	Probability of scenario ω.

4.3.2 MOS Model Constraints

In this section, the model constraints are presented. The constraints of the MOS model are a modification of the constraints for the MOD model described section 3.2.2 after adding a subscript ω to the second-stage decisions.

Material balance constraints: Eq. (4.17) represents the mass balance for oil processing plant. Where, the input and processing quantities are of first-stage decisions type. Eq.(4.18) indicates that the output from each oil processing plant depends on the realization of the uncertain parameters; scenario ω .

$$P_{st}^{hc} X_{st}^{h} + X_{st-1}^{h+} = X_{st}^{c} + X_{st}^{h+} \qquad \forall \quad s, c, t \qquad 4.17$$

$$\sum_{r} X_{sr\omega t}^{c} + \sum_{u} X_{su\omega t}^{c} = X_{st}^{c} \qquad \forall \quad s, c, \omega, t \qquad 4.18$$

Eq. (4.19) represents the mass balance for gas plant. Where, the input and processing quantities are of first-stage decisions type. Eq.(4.20) represents that the output from each gas plant depends on the realization of the uncertain parameters; scenario ω .

$$\sum_{n} P_{at}^{ng} Y_{at}^{b} + \sum_{n} Y_{at-1}^{n+} = Y_{at}^{g} + \sum_{b} Y_{at}^{n+} \qquad \forall \quad a, g, t \qquad 4.19$$

$$\sum_{f} Y_{af\omega t}^{g} + \sum_{d} Y_{ad\omega t}^{g} + \sum_{u} Y_{au\omega t}^{g} = Y_{at}^{g} \qquad \forall \quad a, g, \omega, t \qquad 4.20$$

Eqs. (4.21) and (4.22) represent the mass balance for refinery plant under each scenario ω.

$$\sum_{s,c} P_{srt}^{co} X_{sr\omega t}^{c} + \sum_{c} X_{r\omega t-1}^{c+} = X_{r\omega t}^{o} + \sum_{c} X_{r\omega t}^{c+} \qquad \forall \quad r, o, \omega, t \qquad 4.21$$

$$\sum_{u} X^{o}_{ru\omega t} + \sum_{b} X^{o}_{rb\omega t} = X^{o}_{r\omega t} \qquad \forall \quad r, o, \omega, t \qquad 4.22$$

Eqs. (4.23) and (4.24) balance the gas products fractionating quantities with the output from fractionation plant to each demand node for each scenario ω.

$$\sum_{a} P^{g}_{aft} Y^{g}_{af\omega t} + Y^{g+}_{f\omega t-1} = Y^{g}_{f\omega t} + \ Y^{g+}_{f\omega t} \qquad \forall \ f, g, \omega, t \qquad 4.23$$

$$\sum_{u} Y^{g}_{fu\omega t} + \sum_{e} Y^{g}_{fe\omega t} + \sum_{d} Y^{g}_{fd\omega t} = Y^{g}_{f\omega t} \qquad \forall \ f, g, \omega, t \qquad 4.24$$

While, Eq. (4.25) states the material balance in storage bulk plants for each realization ω.

$$\sum_{r} X^{o}_{rb\omega t} + X^{o+}_{b\omega t-1} = \sum_{e} X^{o}_{be\omega t} + \sum_{d} X^{o}_{bd\omega t} + X^{o+}_{b\omega t} \qquad \forall \ \ b, \ o, \omega, t \qquad 4.25$$

Plant capacity constraints: Eqs. (4.22 & 4.27) represent the capacity of oil processing plant and gas plants, respectively. The two constraints are related to the first stage and do not depend of the scenarios.

$$X^{h}_{st} + X^{h+}_{st-1} \qquad \leq \qquad CP_s \qquad \forall \ s, t \qquad 4.26$$

$$\sum_{n} Y^{n}_{at} + \sum_{n} Y^{n+}_{at-1} \qquad \leq \qquad CP_a \qquad \forall \ a, t \qquad 4.27$$

Eqs. (4.29 - 4.31) represent the capacity of refinery plant, fractionation plant, and international oil and gas terminals, respectively, for each scenario ω.

$$\sum_{s,c} X^{c}_{sr\omega t} + \sum_{c} X^{c+}_{r\omega t-1} \qquad \leq \ CP_r \qquad \forall \ r, \omega, t \qquad 4.28$$

$$\sum_{a,g} Y_{af\omega t}^{g} + Y_{f\omega t-1}^{+g} \leq CP_f \qquad \forall\ f, \omega, t \qquad 4.29$$

$$\sum_{r,o} X_{ru\omega t}^{o} + \sum_{s,c} X_{su\omega t}^{c} \leq \mathrm{CP}_u \qquad \forall\ u, \omega, t \qquad 4.30$$

$$\sum_{a,g} Y_{au\omega t}^{g} + \sum_{f,g} Y_{fu\omega t}^{g} \leq CP_u \qquad \forall\ u, \omega, t \qquad 4.31$$

Route capacity constraints: The constraints of each route in the network are represented by Eqs. (4.32-4.45) for each scenario ω.

$$X_{su\omega t}^{c} \leq AC_{su} \qquad \forall\ s, u, c, \omega, t \qquad 4.32$$

$$X_{sr\omega t}^{c} \leq AC_{sr} \qquad \forall\ s, u, c, \omega, t \qquad 4.33$$

$$X_{ru\omega t}^{o} \leq AC_{ru} \qquad \forall\ r, u, o, \omega, t \qquad 4.34$$

$$X_{rb\omega t}^{o} \leq AC_{rb} \qquad \forall\ r, b, o, \omega, t \qquad 4.35$$

$$X_{be\omega t}^{o} \leq AC_{be} \qquad \forall\ b, e, o, \omega, t \qquad 4.36$$

$$X_{bd\omega t}^{o} \leq AC_{bd} \qquad \forall\ b, d, o, \omega, t \qquad 4.37$$

$$X_{ku\omega t}^{o} \leq AC_{ku} \qquad \forall\ k, u, o, \omega, t \qquad 4.38$$

$$Y_{af\omega t}^{g} \leq AC_{af} \qquad \forall\ a, f, g, \omega, t \qquad 4.39$$

$$Y_{ad\omega t}^{g} \leq AC_{ad} \qquad \forall\ a, n, g, \omega, t \qquad 4.40$$

$$Y_{au\omega t}^{g} \leq AC_{au} \qquad \forall\ a, u, g, \omega, t \qquad 4.41$$

$$Y^{g}_{fe\omega t} \leq AC_{fe} \quad \forall\ f,e,g,\omega,t \qquad 4.42$$

$$Y^{g}_{fd\omega t} \leq AC_{fd} \quad \forall\ f,d,g,\omega,t \qquad 4.43$$

$$Y^{g}_{fu\omega t} \leq AC_{fu} \quad \forall\ f,u,g,\omega,t \qquad 4.44$$

$$Y^{g}_{ku\omega t} \leq AC_{ku} \quad \forall\ k,u,g,\omega,t \qquad 4.45$$

Demand constraints: Eq. (4.46) represents the international demand for crude oil type c at each international terminal u for each scenario ω.

$$\sum_{s} X^{c}_{su\omega t} - X^{c+}_{u\omega t} + X^{c-}_{u\omega t} = D^{c}_{u\omega t} \quad \forall\ u,c,\omega,t \qquad 4.46$$

Eqs. (4.47-4.49) represent the domestic, industry and international demands for oil refined products respectively, for each scenario ω.

$$\sum_{b} X^{o}_{be\omega t} - X^{o+}_{e\omega t} + X^{o-}_{e\omega t} = D^{o}_{e\omega t} \quad \forall\ e,o,\omega,t \qquad 4.47$$

$$\sum_{b} X^{o}_{bd\omega t} - X^{o+}_{d\omega t} + X^{o-}_{d\omega t} = D^{o}_{d\omega t} \quad \forall\ d,o,\omega,t \qquad 4.48$$

$$\sum_{r} X^{o}_{ru\omega t} - X^{o+}_{u\omega t} + X^{o-}_{u\omega t} = D^{o}_{u\omega t} \quad \forall\ u,o,\omega,t \qquad 4.49$$

The domestic, industry, and international demands for gas products are represented by Eqs. (4.50-4.52), respectively for each scenario ω.

$$\sum_{f} Y^{g}_{fe\omega t} + \sum_{u} Y^{g}_{ue\omega t} - Y^{g+}_{e\omega t} + Y^{g-}_{e\omega t} = D^{g}_{e\omega t} \quad \forall\ e,g,\omega,t \qquad 4.50$$

$$\sum_{a} Y^{g}_{ad\omega t} + \sum_{f} Y^{g}_{fd\omega t} + \sum_{u} Y^{g}_{ud\omega t} - Y^{g+}_{d\omega t} + Y^{g-}_{d\omega t} \quad = \quad D^{g}_{d\omega t} \quad \forall\ d, g, \omega, t \qquad 4.51$$

$$\sum_{a} Y^{g}_{au\omega t} + \sum_{f} Y^{g}_{fu\omega t} - Y^{g+}_{u\omega t} + Y^{g-}_{u\omega t} \quad = \quad D^{g}_{u\omega t} \quad \forall\ u, g, \omega, t \qquad 4.52$$

OPEC quota Constraint: For each scenario ω, the amount of international sales of crude oil of all types are limited by the OPEC quota specified to each country at any period of time t; Eq. (4.53).

$$\sum_{s,u,c} X^{c}_{su\boldsymbol{\omega}t} \quad \leq \quad OPEC_{t} \quad \forall \omega, t \qquad 4.53$$

Service level constraints: For each scenario ω, service level at each time interval t is defined for oil and gas separately as the sales at demand nodes divided by the total demand; Eq. (4.54-4.57), respectively.

$$SLO_{\omega t} = \frac{\sum_{s,u,c}[X^{c}_{su\omega t} - X^{c+}_{u\omega t}] + \sum_{r,u,o}[X^{o}_{ru\omega t} - X^{o+}_{u\omega t}] + \sum_{b,e,o}[X^{o}_{be\omega t} - X^{o+}_{e\omega t}] + \sum_{b,d,o}[X^{o}_{bd\omega t} - X^{o+}_{d\omega t}]}{\sum_{u,c} D^{c}_{u\omega t} + \sum_{u,o} D^{o}_{u\omega t} + \sum_{e,o} D^{o}_{e\omega t} + \sum_{d,o} D^{o}_{d\omega t}} \quad \forall\ \omega, t \qquad 4.54$$

$$SLG_{\omega t} = \frac{\sum_{a,d,g}\left[Y^{g}_{ad\omega t} - Y^{g+}_{d\omega t}\right] + \sum_{a,u,g}\left[Y^{g}_{au\omega t} - Y^{g+}_{u\omega t}\right] + \sum_{f,e,g}\left[Y^{g}_{fe\omega t} - Y^{g+}_{e\omega t}\right] + \sum_{f,d,g}\left[Y^{g}_{fd\omega t} - Y^{g+}_{d\omega t}\right] + \sum_{f,u,g}\left[Y^{g}_{fu\omega t} - Y^{g+}_{u\omega t}\right]}{\sum_{d,g} D^{g}_{d\omega t} + \sum_{u,g} D^{g}_{u\omega t} + \sum_{e,g} D^{g}_{e\omega t}} \quad \forall\ \omega, t \qquad 4.55$$

$$MTSL \ \leq SLO_{\omega t} \quad \forall\ \omega,\ t \qquad 4.56$$

$$MTSL \ \leq SLG_{\omega t} \quad \forall\ \omega, t \qquad 4.57$$

4.3.3 MOS Model Objective Functions

The total cost formula involves two main parts: a deterministic term represented by the first stage and a stochastic term represented by the expected value of the second stage problems.

$$
\begin{aligned}
\text{Minimize}\, f1 = \sum_{t=1}^{T} (1+dr)^{-(t-1)} \Bigg\{ & \sum_{s,h,t} PC_{st}^{h} X_{st}^{h} + \sum_{a,n,t} PC_{at}^{n} Y_{at}^{n} \\
& + \sum_{\omega\in\Omega} \pi_{\omega} \Bigg[\sum_{s,r,c,t} SC_{srt}^{c}\, X_{sr\boldsymbol{\omega}t}^{c} + \sum_{a,f,g,t} SC_{aft}^{g} Y_{af\boldsymbol{\omega}t}^{g} + \sum_{s,u,c,t} CT_{sut}^{c} X_{su\boldsymbol{\omega}t}^{c} \\
& + \sum_{s,r,c,t} CT_{srt}^{c} X_{sr\boldsymbol{\omega}t}^{c} + \sum_{r,u,o,t} CT_{rut}^{o}\, X_{ru\boldsymbol{\omega}t}^{o} + \sum_{r,b,o,t} CT_{rbt}^{o}\, X_{rb\boldsymbol{\omega}t}^{o} \\
& + \sum_{b,e,o,t} CT_{bet}^{o}\, X_{be\boldsymbol{\omega}t}^{o} + \sum_{b,d,o,t} CT_{bdt}^{o}\, X_{bd\boldsymbol{\omega}t}^{o} + \sum_{k,u,o,t} CT_{kut}^{o}\, X_{ku\boldsymbol{\omega}t}^{o} \\
& + \sum_{a,f,g,t} CT_{aft}^{g} Y_{af\boldsymbol{\omega}t}^{g} + \sum_{a,u,g,t} CT_{aut}^{g} Y_{au\boldsymbol{\omega}t}^{g} + \sum_{a,d,g,t} CT_{adt}^{g} Y_{ad\boldsymbol{\omega}t}^{g} \\
& + \sum_{f,u,g,t} CT_{fut}^{g} Y_{fu\boldsymbol{\omega}t}^{g} + \sum_{f,d,g,t} CT_{fdt}^{g} Y_{fd\boldsymbol{\omega}t}^{g} + \sum_{f,u,g,t} CT_{fut}^{g} Y_{fu\boldsymbol{\omega}t}^{g} \\
& + \sum_{f,e,g,t} CT_{fet}^{g} Y_{fe\boldsymbol{\omega}t}^{g} + \sum_{k,u,g,t} CT_{kut}^{g} Y_{ku\boldsymbol{\omega}t}^{g} + \sum_{k,u,o,t} IC_{kt}^{o}\, X_{ku\boldsymbol{\omega}t}^{o} \\
& + \sum_{k,u,g,t} IC_{kt}^{g} Y_{ku\boldsymbol{\omega}t}^{g} + \sum_{s,h,t} HC_{st}^{h}\, X_{st}^{h+} + \sum_{a,n,t} HC_{at}^{n}\, Y_{at}^{n+} + \sum_{r,c,t} HC_{rt}^{c}\, X_{rt}^{c+} \\
& + \sum_{b,o,t} HC_{bt}^{o}\,,\, X_{b\boldsymbol{\omega}t}^{o+} + \sum_{f,g,t} HC_{ft}^{g}\, Y_{f\boldsymbol{\omega}t}^{g+} + \sum_{e,o,t} (w_{et}^{o+} X_{e\boldsymbol{\omega}t}^{o+} + w_{et}^{o-} X_{e\boldsymbol{\omega}t}^{o-}) \\
& + \sum_{d,o,t} (w_{dt}^{o+} X_{d\boldsymbol{\omega}t}^{o+} + w_{dt}^{o-} X_{d\boldsymbol{\omega}t}^{o-}) + \sum_{u,o,t} (w_{ut}^{o+} X_{u\boldsymbol{\omega}t}^{o+} + w_{ut}^{o-} X_{u\boldsymbol{\omega}t}^{o-}) \\
& + \sum_{e,g,t} \left(w_{et}^{g+} Y_{e\boldsymbol{\omega}t}^{g+} + w_{et}^{g-} Y_{e\boldsymbol{\omega}t}^{g-}\right) + \sum_{d,g,t} \left(w_{dt}^{g+} Y_{d\boldsymbol{\omega}t}^{g+} + w_{dt}^{g-} Y_{d\boldsymbol{\omega}t}^{g-}\right) \\
& + \sum_{u,g,t} \left(w_{ut}^{g+} Y_{u\boldsymbol{\omega}t}^{g+} + w_{ut}^{g-} Y_{u\boldsymbol{\omega}t}^{g-}\right) + \sum_{u,c,t} (w_{ut}^{c+} X_{u\boldsymbol{\omega}t}^{c+} + w_{ut}^{c-} X_{u\boldsymbol{\omega}t}^{c-}) \Bigg] \Bigg\}
\end{aligned}
$$

The deterministic term involves processing costs at oil processing plant and gas plant. The expected cost of the second stage involves transforming and separation costs, purchasing cost of oil and gas products from international markets, transportation cost, holding costs, and penalty costs of producing over and under the specified demand.

Equation below represents the expected **total revenue** as the return obtained from selling of crude oil, oil products, and gas products locally and internationally.

$$
\begin{aligned}
&Maximize\ \ f2 \\
&= \sum_{t=1}^{T} (1+dr)^{-(t-1)} \sum_{\omega \in \Omega} \pi_\omega \Bigg[\sum_{s,u,c,t} SP^{c}_{u\omega t}(X^{c}_{su\omega t} - X^{c+}_{u\omega t}) \\
&+ \sum_{r,u,o,t} SP^{o}_{u\omega t}(X^{o}_{ru\omega t} - X^{o+}_{u\omega t}) + \sum_{b,e,o,t} SP^{o}_{e\omega t}(X^{o}_{be\omega t} - X^{o+}_{e\omega t}) \\
&+ \sum_{b,d,o,t} SP^{o}_{d\omega t}(X^{o}_{bd\omega t} - X^{o+}_{d\omega t}) + \sum_{a,u,g,t} SP^{g}_{u\omega t}\left(Y^{g}_{au\omega t} - Y^{g+}_{u\omega t}\right) \\
&+ \sum_{a,d,g,t} SP^{g}_{d\omega t}\left(Y^{g}_{ad\omega t} - Y^{g+}_{d\omega t}\right) + \sum_{f,u,g,t} SP^{g}_{u\omega t}\left(Y^{g}_{fu\omega t} - Y^{g+}_{u\omega t}\right) \\
&+ \sum_{f,d,g,t} SP^{g}_{d\omega t}\left(Y^{g}_{fd\omega t} - Y^{g+}_{d\omega t}\right) + \sum_{f,e,g,t} SP^{g}_{e\omega t}\left(Y^{g}_{fe\omega t} - Y^{g+}_{e\omega t}\right) \Bigg]
\end{aligned}
$$

The service level objective function is defined below.

Maximize $f3 = MTSL$

4.4 Applied Case Study: MOS Model

In this study, two uncertain parameters have been considered: the domestic demand and the international prices. The domestic demand is selected due to: it has been noticed a huge increase in the domestic demand of the petroleum products. This increase is due to the variations or the increases of population growth of Kingdom of Saudi Arabia. The international price is selected to be consistent with the sharp reduction in the selling prices of petroleum products in the period 2014-2016. The reduction of petroleum prices is due the huge production of petroleum products over the world demand.

To evaluate and demonstrate the utility of the MOS model, in addition to the real data of the Kingdom of Saudi Arabia HCSC stated in section 3.3, the values of low, base, and high scenarios of uncertain parameters with their associated probabilities were specified to be consistence with the Saudi Arabia case study and validated with experts of the ARAMCO company. Where, the high demand scenario considers a 20% higher than the current demand (one in the base scenario) for oil and gas products, while the low demand scenario assumes that the demand is 20% lower than the current demands. The high price scenario considers a 20% higher than the real prices of petroleum products, while the low price scenario assumed to be 20% lower than the one in the base scenario.

Table 4.2 Probabilities of the uncertain parameters

Stochastic Parameter	**Realizations**	**Probability**
	Low	0.25
Domestic demand	base	0.50
	High	0.25
	Low	0.25
International price	base	0.50
	High	0.25

For scenarios construction, the probabilities of the three possible scenarios (low, base, and high) for each stochastic parameter are assumed. Table 4.2 shows the probability of the three possible scenarios (High, base, and Low) for each uncertain parameter. The joint probabilities of 9 scenarios are generated by multiplying the probabilities of each uncertain parameter assuming that demand and price are independent of each other as shown in scenario tree Fig. 4.1. For example, if demand is high, price could be (high, base, low). For demand, it is assumed a complete dependence for all products. for example, one scenario of high demand for one product implies in high demand to the other products. Similar pattern is assumed for prices.

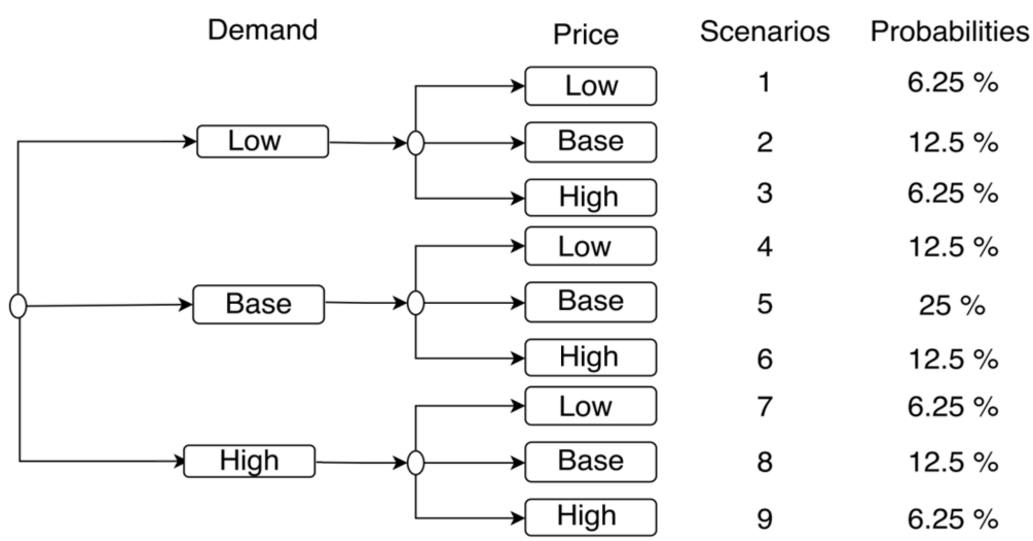


Figure 4.1 Scenario tree

Full dependency between scenarios during time periods was assumed. In other words, if the first period was high price – high demand the subsequent periods will be same for short planning periods. This assumption has been validated using historical records of OPEC basket price of crude oil during 171 month starting from January 2003 to May 2017 (“ OPEC Basket Price,”2017). **Error! Reference source not found.** show that the average i ncrease and decrease in oil price from month to the next are 3.97% and 3.38%, respectively, which less than 20% that assumed in scenario construction.

Table 4.3 Statistics regarding crude oil OPEC basket price

Study period :	from 02//01/2003 to 11/05/2017
Total number of months:	171 months
Months with change over 20%:	8 months
Average increase in oil price:	3.97 %
Average decrease in oil price:	-3.38 %

Referred to the Kingdom of Saudi Arabia HCSC network, the first stage decisions are the input stream to oil processing plants and gas plants and amount of oil and natural gas processing at the first echelon. The recourse actions (second stage decisions) are the processing in the second echelon, the flow quantities between each node, and the importation and exportation quantities.

4.4.1 Results and Discussion of MOS Model

The deterministic equivalent of the two-stage stochastic model was coded based on improved augmented ε-constraint algorithm in the GAMS 24.1.2-32 bit and solved using the CPLEX 13.3 commercial solver. The statistics of stochastic model are illustrated in Table 4.4.

Table 4.4 MOS model statistics

Blocks of Equations	72	Single Equations	16662
Blocks of Variables	51	Single Variables	24880
CPU time (s)	3720	Non-zero Elements	109732

The obtained Pareto optimal solutions along with their corresponding tactical decisions for the MOS model are analyzed for each realization of the uncertain parameters. Table 4.5 summarizes the payoff results obtained by the lexicographic optimization of the three objectives.

Table 4.5 Payoff results of the MOS model

	Total cost ($ M/3 months)	Total revenue ($ M/3 months)	Service level
Minimize total cost	6842	41453	0.825
Maximize total revenue	7630	41681	0.922
Maximize service level	6902	41529	0.938

The Pareto optimal solutions are generated using a systematic search based on dividing the range of the total revenue and service level into 100 grid points. Fig. 4.2 represents the surface plot of Pareto optimal solutions of the three objectives for the MOS model. It has a similar shape as for the MOD model.

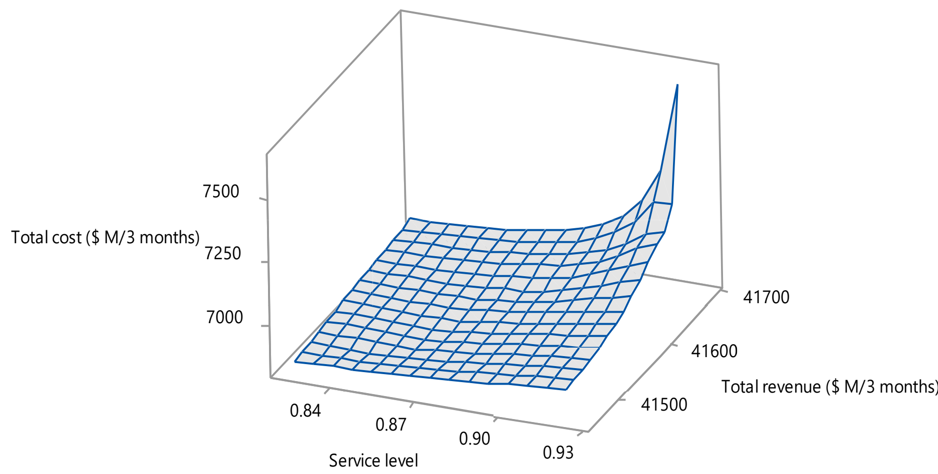


Figure 4.2 3D Pareto curve for MOS model

For the purpose of comparison, one efficient point is selected from the set of Pareto optimal set. This point is chosen using TOPSIS with equally weighted for the three objectives.

The values of the objective functions, oil and gas processing quantities, and flow quantities for both the MOD and MOS models are listed in Table 4.6 and Table 4.6 respectively. Comparing the two plans regarding oil and gas processing and imports, the MOS model results in a reduction of oil processing, oil refining, and gas fractioning. To compensate for this reduction, the model increases the oil and gas imports from international.

The MOS model experiences higher total cost and lower total revenue. The reason behind this trend is that the MOS model plans for several scenarios while the MOD model is optimizing for one scenario. Planning for more scenarios result in more constraints. Adding more constraints leads to a reduction in the feasible region. Accordingly, total cost increases, while revenue decreases. The service level is high for the MOD model because the demand values are assumed to be known and fixed and most of it could be satisfied.

The reduction in service level values for the MOS model are due to the variation and the uncertainty in demand.

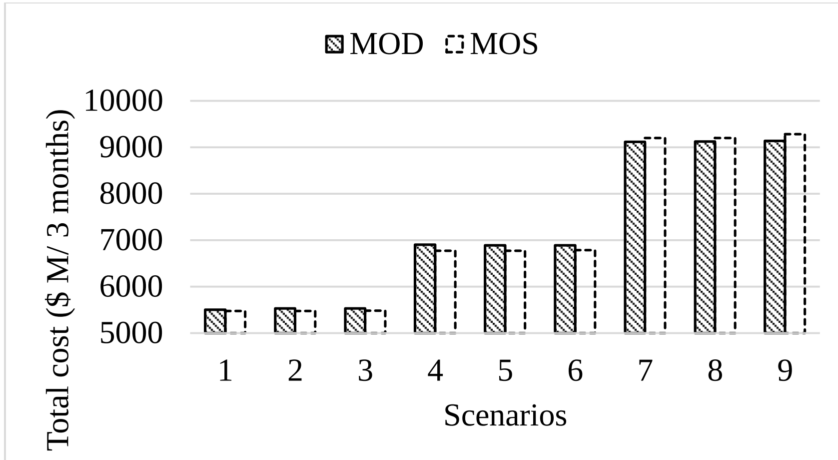
Table 4.6 Preferred plan from the MOD model

Total cost =	$6887 M/3 months	Oil refining =	2.82 MBL/day
Total revenue =	$ 41676 M/3 months	Oil imports =	0.28 MBL/day
Service level =	0.933	Gas imports =	257 Mcft/day
Oil processing =	10.27 MBL/day	Gas fractioning=	1957 Mcft/day

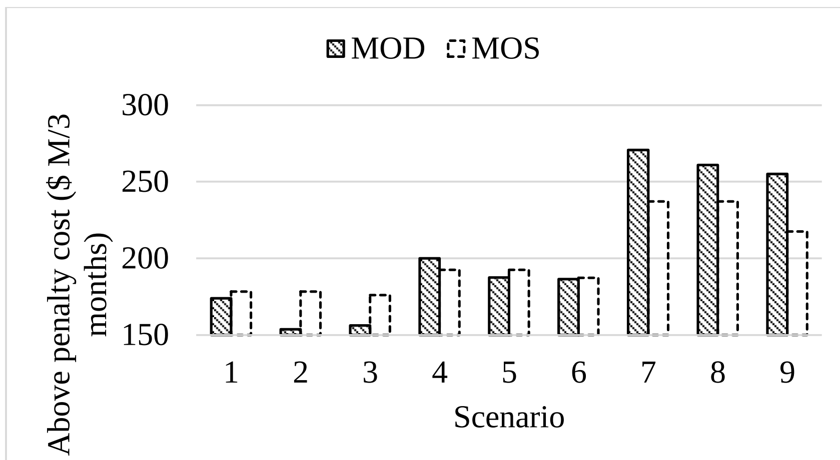
Table 4.7 Preferred plan from the MOS model

Total cost =	$ 7062 M/3 months	Oil refining =	2.66 MBL/day
Revenue =	$ 41651 M/3 months	Oil imports =	0.3389 MBL/day
Service level =	0.917	Gas imports =	274 Mscft/day
Oil processing =	10.10 MBL/day	Gas fractioning =	1912 Mscft/day

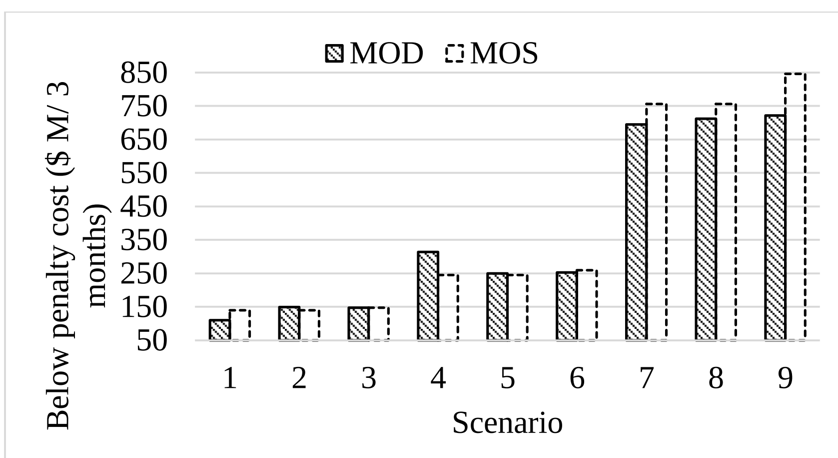
To analyze and compare the results of both the MOS model and the MOD model, The MOS is solved for each scenario individually and plotted in conjunction with results from MOS model. The variation of costs for each realization of uncertain parameters for both MOS and MOD models is illustrated in Fig. 4.3 (a-c). For the MOS model, the total cost is high for the last three scenarios (7, 8, and 9) due to the high values of demands in these scenarios as shown in Fig. 4.3(a).



(a) Total cost



(b) Penalty cost of production above demands

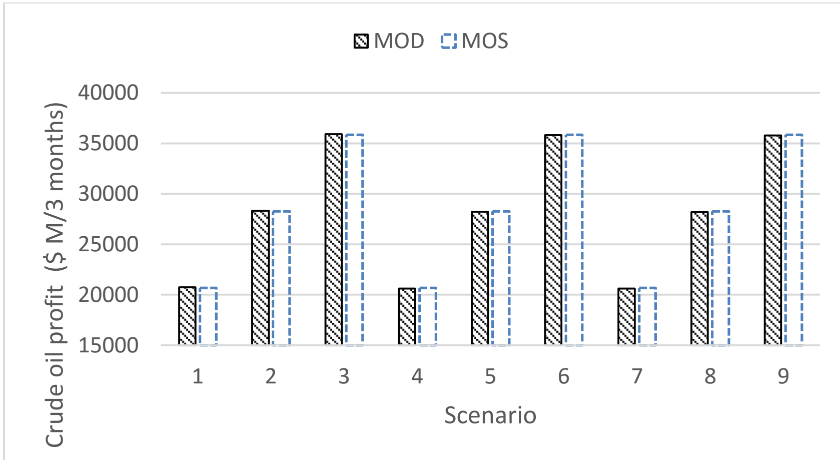


(c) Penalty cost of production below demands

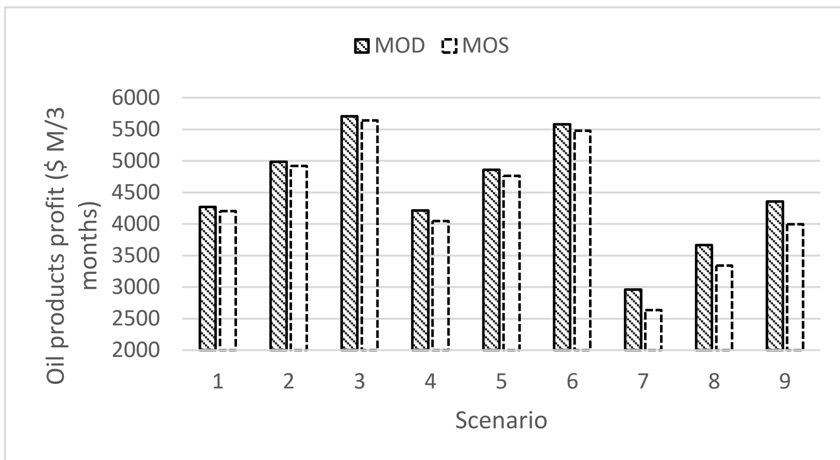
Figure 4.3 Variation of cost elements with scenarios for MOD and MOS models

The MOD model process more oil products per scenario. Consequently, total cost for scenarios with low and base demand is less for MOS than MOD, because of the reduction in penalty of producing less than the demand. While, scenarios with high demand situation is reversed because the cost of production, processing, and transportation associated with the MOD is less than that of the MOS. This increase is due to satisfying the increases in the demand from the below productions as indicated in Fig. 4.3 (c).

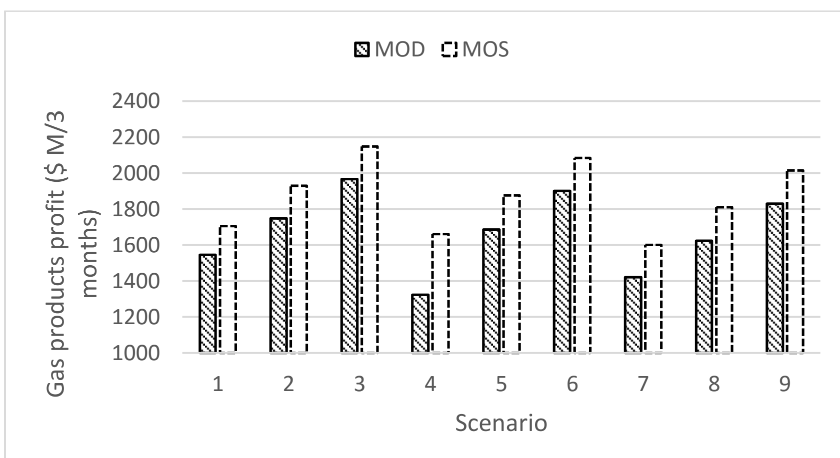
The penalty cost of below production increases for scenarios with high demands because the whole market demand cannot be satisfied from local production instead the demand is fulfilled from under production which leads to high below penalty costs. It is clear that, the selling price has slightly effect on the cost.



(a) Crude oil



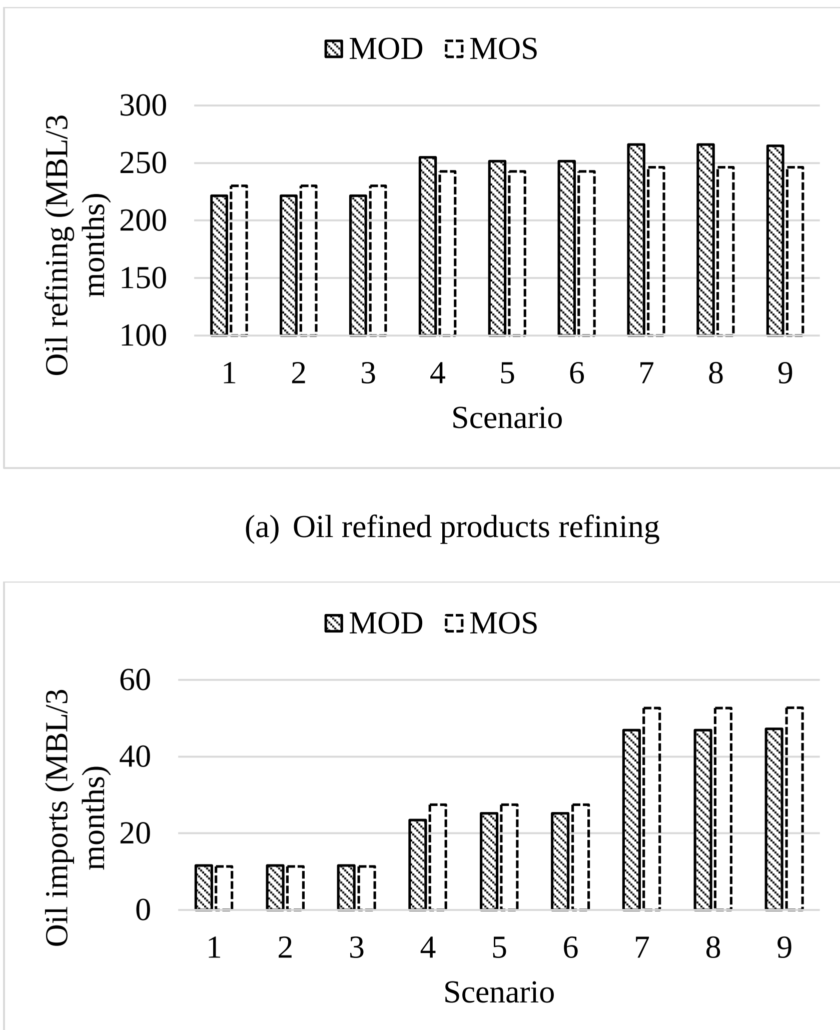
(b) Oil products



(c) Gas products

Figure 4.4 Profit with respect to each scenario for MOD & MOS models.

The profit under each scenario for each product types is illustrated in Fig. 4.4. The best results for the total revenue were found in the scenarios with high prices (3, 6, and 9). This finding indicates that the model is sensitive to the uncertain parameters and that the prices parameter had a greater impact on total revenue than the demands uncertainty had. The low revenue is recorded for scenario 1 because it represents scenario with low demand and low price values. The results show that the best plan can be obtained if the scenario of high demand and high price is occurred, scenario 9.



(a) Oil refined products refining

(b) Oil refined products imports

Figure 4.5 Oil refining and imports versus scenarios for MOD & MOS models

The oil refining at local refinery plants and gasoline and diesel imports for both MOS and MOD are shown in Fig. 4.5. The oil refining and oil imports record high values in the scenarios of high demand. The imports decrease for the scenarios with low demand values because the low demand can be satisfied from local refining instead of imports. Comparing results of the MOS and MOD models, oil import is very high for the stochastic model especially for the scenario of base and high demands while oil refining is low. In general, the MOD model records higher local reefing than the MOS model. Instead of the low local oil refining, the MOS model records high oil imports and high under demands.

4.4.2 Sensitivity Analysis of MOS Model

In real situations, there is an elastic relationship between price and demand. For example, as price decreases, this will encourage customers to buy more. The above fact is analyzed by changing the probabilities of uncertain parameters in Fig. 4.1. Three cases are considered and compared. Case I; the one studied in the MOS model above. Case II, high probability (0.5) is assigned to scenarios with (low demand –high price). Case III, high probability (0.5) of scenarios with (high demand–low price) is assumed.

The preferred plans of the three cases are concluded in Table 4.8 and Table 4.9 based on TOPSIS. Plan of case II is more profitable because high probability is assigned to scenarios of high prices. In addition, this plan shows more imports from international market than Case III, because the probability of low demand is high and then no need to operate or fully utilize local resources. On the other hand, plan of case III leads to higher oil processing and refining and also higher gas fractioning because in this case, high probability is assigned for scenarios of high demands. Case II records higher service level than Case III since high probability is assigned for low demand and high prices which means that most of demand could be satisfied.

Table 4.8 Preferred plan from case II using MOS model.

Total cost =	$ 6766 M /3 months	Oil refining =	2.64 MBL/day
Revenue =	$ 43514 M/3 months	Oil imports =	0.346 MBL/day
Profit =	$ 36747 M/3 months	Gas processing	12395 Mscft/day
Service level =	0.922	Gas imports =	272 Mscft/day
Oil processing =	10.08 MBL/day	Gas fractioning=	1935 Mscft/day

Table 4.9 Preferred plan from case III using MOS model.

Total cost =	$ 7559 M /3 months	Oil refining =	2.73832 MBL/day
Revenue =	$ 39744 M /3 months	Oil imports =	0.322 MBL/day
Profit =	$ 32185 M /3 months	Gas production =	12126 Mscft/day
Service level =	0.901	Gas imports =	249 Mscft/day
Oil processing =	10.21 MBL/day	Gas fractioning	1991 Mscft/day

Fig. 4.6 shows the total costs for the three cases under each scenario. As expected, case III shows high cost for the scenarios of base and high demands (4,5,6,7,8, and 9), this is a result of increasing the penalty costs of producing below demand since in this case high probability is assigned for scenarios of high demands. Case II, shows high cost in scenarios of low demands (1,2, and 3) because in this case low demand is given higher probability.

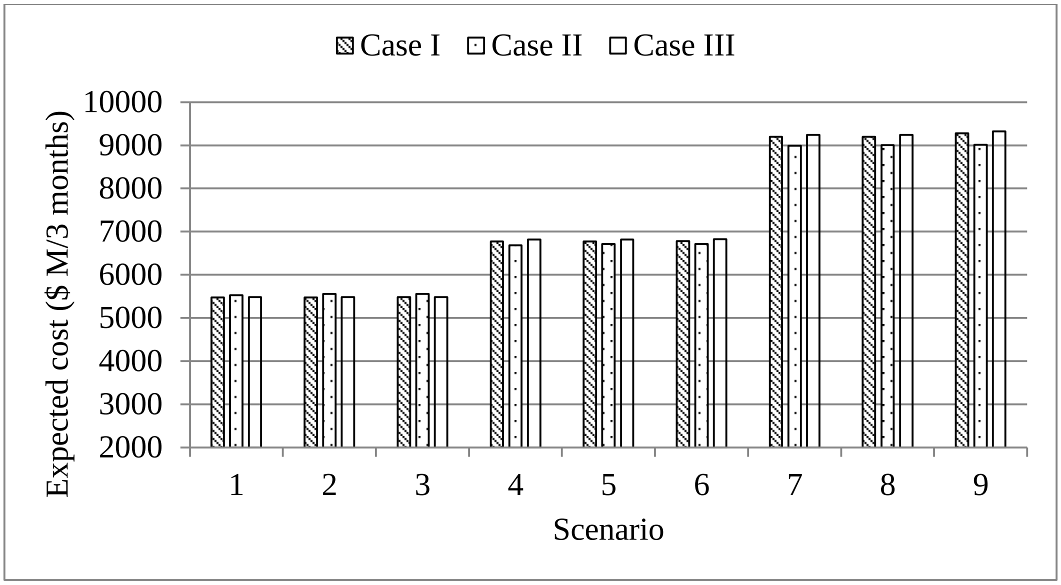


Figure 4.6 Total cost for oil and gas based on MOS model for the three cases

Fig. 4.7 shows the total revenue for the three cases under each scenario. Case II shows slightly high revenue in most of the scenarios, this is a result of high probability assigned for high price and low demand scenarios.

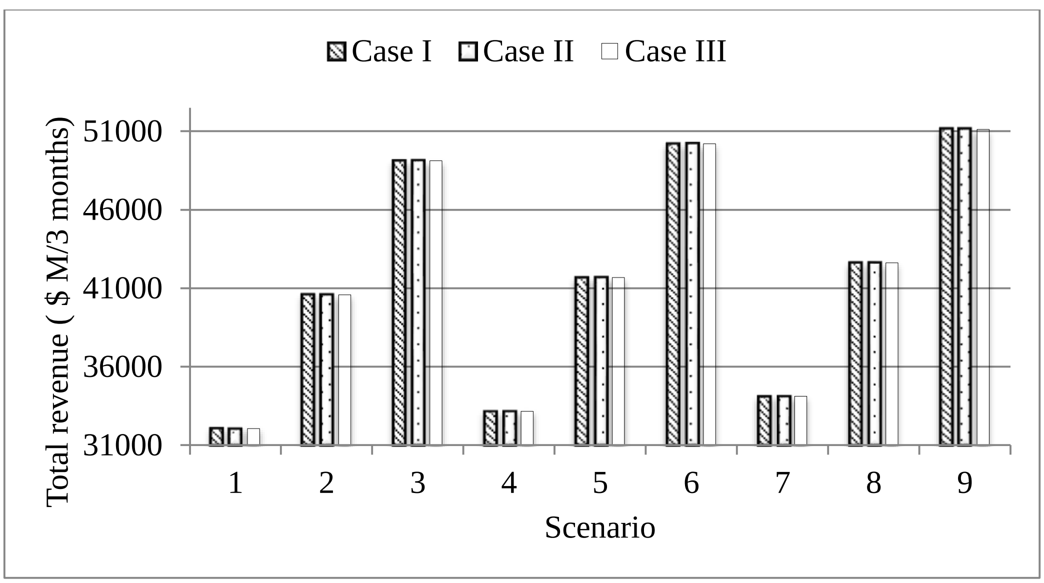


Figure 4.7 Total revenue for oil and gas based on MOS model for the three cases

Fig. 4.8 represents the average utilization of refinery plants for the three cases under each scenario. Case III results in higher utilization of refinery plants than other cases for all scenarios followed by case I. This increase in the utilization is due to high probability that is assigned for scenarios of high demand. Therefore, more production is needed to satisfy the increases in demand.

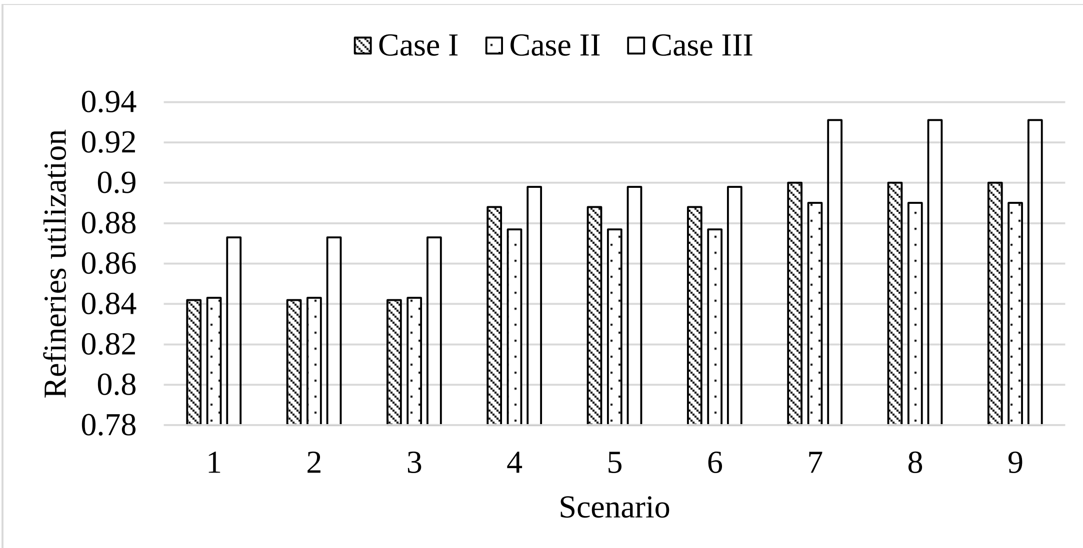


Figure 4.8 Refinery plants utilizations based on MOS model for the three cases

4.5 Conclusion

In this chapter, a multi-objective stochastic (MOS) model of an integrated HCSC has been formulated for tactical planning considering uncertainties in demand and prices. Uncertain parameters are represented as a finite set of scenarios and the problem is formulated using a two-stage stochastic. The proposed MOS helps in assessing the trade-off among different objectives of the Saudi Arabia downstream HCSC and guides the decision maker to choose the preferred tactical decision variables among the Pareto optimal solutions under uncertain market conditions.

In general, it is concluded that uncertainties of demand and prices have a great impact on the tactical decisions of the oil and gas supply chain. Uncertainty in domestic demand showing a greater impact on the oil and gas processing, exportations, and importations decisions. On the other hand, price has slightly effect on the total cost, oil and gas productions, and import quantities. Price has a greater impact on total revenue than the demand. The plans obtained by the MOS model is compared with the plans obtained by the MOD model. The MOS model records low local processing of oil and gas compared to the MOD model. The MOS model is more robust against the variations in the uncertain parameters.

A sensitivity analysis was conducted on the MOS model under three different market situations. Where, high probability was assigned for scenarios of base demand and price in case I. High probability is assigned for scenarios of low demand and high price; case II. High probability is assigned for scenarios of high demand and low price; case III. The main conclusion after studying and analyzing the three cases is that, case III is the worst plan and if this plan happened, it will cost Kingdom of Saudi Arabia high costs and the cash flow will be very low. However, the local processing of both oil and gas is very high which leads to more degradation of the oil and gas reserves. It is noted that the MOS model satisfied most of international, local, and industries demand from under production for most of the scenarios without considering the high penalty of satisfying the demand from under production which leads to high total costs in most of scenarios.

Although this model is an attempt to solve the problems of the deterministic model still it has some limitations. In scenario construction full dependency between scenarios over planning period has been assumed. Even this assumption proves to be valid but still some dependency exists. In addition to the assumption of independency between scenario parameters. In real life the values of prices and/or demand may not be independent. Price can take different values during the planning period (from period to another) and a dependency exist between these values based on market conditions. Also, the MOS model did not consider the risk of exceeding a certain limit of costs and/or the risk of not exceeding a desired levels of revenue. This problem need to be addressed using risk measures in the next chapter.

CHAPTER 5

MULTI-OBJECTIVE RISK MODEL

5.1 Introduction

In this chapter, the MOS model formulated in chapter four is extended to incorporate the risk of uncertainty and the risk of exceeding certain limit of cost or not exceeding certain limit of revenue. In two-stage stochastic programming approach, the expected value of specific objective is optimized. Accordingly, the optimization process must optimize the model that contains distribution function (e.g., the expected value). Therefore, stochastic programming contains uncertain parameters in its objective function. In this situation, the optimization of the objective functions is a risk neutral since the decision maker preference is not considered. The main disadvantage of this process is the ignoring of the other parameters depicting the distribution. For instance, the probability of exceeding certain limit of cost or not exceeding certain limit of revenue may happen in some scenarios. Therefore, during modeling under uncertainty, the effect of these risks in addition to economic goals must be considered simultaneously. To satisfy the above-mentioned aim, a term to control and mitigate the risk must be added to either the objective function and/or the constraints.

In this chapter, we explain the idea of taking into consideration the decision maker preference through extending the MOS model to include Conditional Value at Risk (CVaR) as a risk measure. The proposed model is multi-objective risk (MOR) model. The utility of the MOR model will be evaluated using the Kingdom of Saudi Arabia HCSC case and the effect of incorporating the risk measure is compared with the MOS model.

To achieve the goals, the rest of this chapter is organized as follows: section 5.2 introduces the well-known risk measures. Section 5.3 contains the multi-objective risk model formulation. The applicability of the MOR model is tested using the Saudi Arabia HCSC case in section 5.4. A sensitivity analysis about risk parameters such as risk confidence level and risk level are conducted in section 5.4. The chapter is closed by conclusion in section 5.5.

5.2 Risk Measures

The risk of uncertainty in stochastic programming is quantified and mitigated through many risk measures (Conejo et al., 2010): variance, shortfall probability, expected shortage, Value at Risk (VaR) and Conditional Value at Risk (CVaR). The VaR and CVaR risk measures are discussed in the following subsections.

5.2.1 Value at Risk (VaR)

The VaR, is the threshold value which guarantees that the probability of having a scenario with an objective function value beyond is less than (1-α). For minimization, as instance, VaR equal to threshold value to ensure that the probability of the scenarios with costs more than the threshold value is less than (1-α). The mathematical representation of incorporating the VaR into the two stage stochastic problem stated in Eqs (4.7 -4.10) is shown below:

$Maximize_{x,y(\omega),VaR,\varphi(\omega)}$

$$(1-\beta)\left(c^T x + \sum_{\omega\in\Omega} \pi(\omega) q(\omega)^T y(\omega)\right) + \beta\, VaR \qquad 5.1$$

subject to

$$Ax = b \qquad 5.2$$

$$T(\omega)x \ + \ W(\omega)y(\omega) = h(\omega), \forall\omega \in \Omega \qquad 5.3$$

$$\sum_{\omega\in\Omega} \pi(\omega)\, \varphi(\omega) \leq 1-\alpha \qquad 5.4$$

$$VaR - \left(c^T x + \ q(\omega)^T y(\omega)\right) \ \leq M\, \varphi(\omega), \forall\omega \in \Omega \qquad 5.5$$

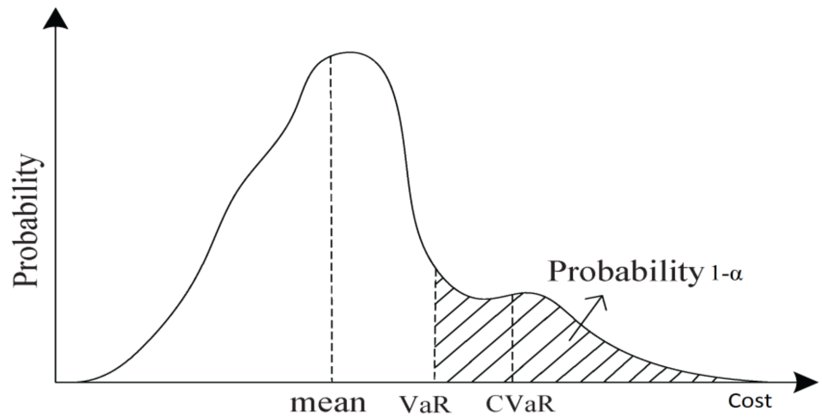
$$\varphi(\omega) \in \{0,1\}, \quad \forall\omega \in \Omega \qquad 5.6$$

$$x \ \in X, \qquad y(\omega) \ \in Y, \quad \forall\omega \in \Omega \qquad 5.7$$

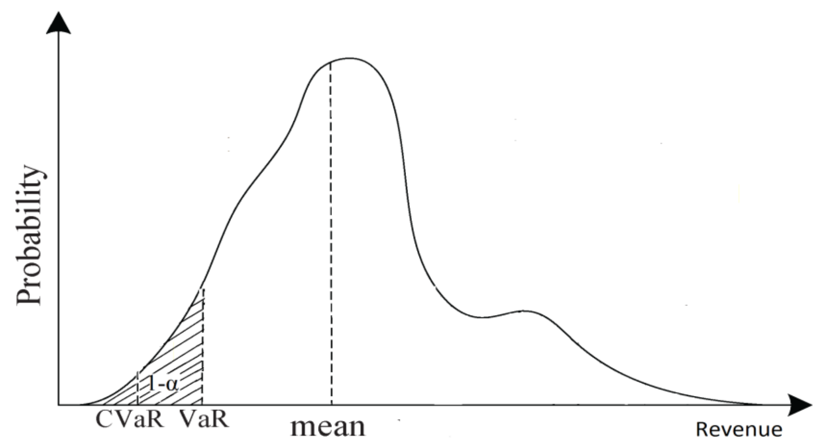
Where $\pi(\omega)$ is the probability of scenario ω, $\varphi(\omega)$ is a binary variable which is different from zero if objective function is less than the target in any scenario ω. β is a weighting risk factor to materialize the tradeoff between expected economic goals and risk (decision maker preference), and M is a big number.

5.2.2 Conditional Value at Risk (CVaR)

The CVaR is the expectation of the scenarios less than the (1-α) quantile of the objective function distribution (i.e., the average of VaR), Fig. 5.1.



a) For minimization problem



b) For maximization problem

Figure 5.1 Curves of both Value-at-Risk and Conditional Value-at-Risk

The mathematical expression for incorporating the CVaR into the two-stage stochastic problem explained in chapter 4 is shown below:

$$Maximize_{x,y(\omega),VaR,\varphi(\omega)}$$

$$(1-\beta)\left(c^T x + \sum_{\omega\in\Omega} \pi(\omega) q(\omega)^T y(\omega)\right) + (\beta)\left(VaR - \frac{1}{1-\alpha}\sum_{\omega\in\Omega} \pi(\omega)\,\varphi(\omega)\right) \quad 5.8$$

$subject\ to$

$$Ax = b \quad 5.9$$

$$T(\omega)x + W(\omega)y(\omega) = h(\omega), \forall\omega \in \Omega \quad 5.10$$

$$VaR - \left(c^T x + q(\omega)^T y(\omega)\right) \leq \varphi(\omega), \forall\omega \in \Omega \quad 5.11$$

$$\varphi(\omega) \geq 0, \forall\omega \in \Omega \quad 5.12$$

$$x \in X, y(\omega) \in Y, \forall\omega \in \Omega \quad 5.13$$

In terms of the multi-objective stochastic optimization case, the CVaR risk measure is incorporated and expressed as follows:

$$Maximize\ f1 = (1-\beta) * \left[C_1^T x + \sum_{\omega\in\Omega} \pi(\omega) q(\omega)_1^T\ y(\omega)\right] + \beta * \left[VaR_1 + \frac{1}{1-\alpha} \sum_{\omega\in\Omega} \pi(\omega)\ \varphi(\omega)_1\right] \quad 5.14$$

$$Maximize f2 = (1-\beta) * \left[C_2^T x + \sum_{\omega\in\Omega} \pi(\omega) q(\omega)_2^T y(\omega)\right] + \beta * \left[VaR_2 + \frac{1}{1-\alpha} \sum_{\omega\in\Omega} \pi(\omega)\ \varphi(\omega)_2\right] \quad 5.15$$

.
.

$$Maximize\ fn = (1-\beta) * \left[C_n^T x + \sum_{\omega\in\Omega} \pi(\omega) q(\omega)_n^T y(\omega)\right] + \beta * \left[VaR_n + \frac{1}{1-\alpha} \sum_{\omega\in\Omega} \pi(\omega)\ \varphi(\omega)_n\right] \quad 5.16$$

$subject\ to$

5.17

$$Ax \leq b$$

$$T(\omega)\, x \ + \ W(\omega)\, y(\omega) \leq h(\omega) \forall\, \omega \in \Omega \tag{5.18}$$

$$\varphi(\omega)_i \quad \geq \quad \left[C_i^T x + \sum_{\omega \in \Omega} \pi^{\omega} q(\omega)_i^T y(\omega)\right] - VaR_i\,, \quad \forall\, \omega \in \Omega, i \in \mathrm{n} \tag{5.19}$$

$$\varphi(\omega)_i \quad \geq \quad 0 \qquad \forall\, \omega \in \Omega, i \in \mathrm{n} \tag{5.20}$$

Where $\varphi(\omega)$ is continuous non negative variable. It is different from zero if objective is less than the target in any scenario ω. CVaR risk measure has been proven to be a coherent risk measure (Conejo et al., 2010) used to control and mitigate the financial risk.

5.3 MOR Model Formulation

In this section, the MOS model is extended to include the risk of uncertainty via adding a coherent risk measure; CVaR. The CVaR constraints are added to the MOS model. The total cost and revenue objective functions are modified to materialize the tradeoffs between risk and the economic goals.

5.3.1 MOR Model Notations

The same notations used in the MOS are utilized for formulating the MOR model. In Table 5.1, deterministic, stochastic decision variables, and parameters of risk are listed.

Table 5.1 Notations of the MOR model

Deterministic variables	
$VaRc$	Auxiliary variable; target or maximum cost the decision maker can accept.
$VaRr$	Auxiliary variable; target or minimum revenue the decision maker can accept.
CVaRc	The expected value of the costs greater than the (1 − α)-quantile of the cost distribution.
CVaRr	The expected value of the revenues smaller than the (1 − α)-quantile of the revenue distribution.
Stochastic variables	
φc^{ω}	Continuous variable related to total cost. It is different from zero if cost is greater than the target in any scenario ω.
φr^{ω}	Continuous variable related to total revenue. It is different from zero if revenue is less than the target in any scenario ω.
Parameters	
β	Risk level; a weighting risk factor used to materialize the tradeoff between expected economic goals and risk.
α	Risk confidence level.

5.3.2 MOR Model Constraints

Material balance, capacity of processing facilities and routes, local, industrial and international demands, service level, and OPEC quota constraints remain the same as in the MOS model. On the contrary, risk constraints related to total cost and total revenue are formulated in Eqs. (5.21- 5.24).

Eq. (5.21) represents the difference between total revenue per scenario and the auxiliary variable $VaRr$. If the total revenue for any scenario is less than the VaR, the variable φr^{ω} is different from zero. However, if the total revenue for any scenario is greater than the threshold value $VaRr$, the variable φr^{ω} is equal to zero as it is limited by Eq. (5.22).

$$\varphi r^{\omega} \geq VaRr - \sum_{t=1}^{T}(1+dr)^{-(t-1)} \left[\sum_{s,u,c,t} SP^{c}_{u\omega t}(X^{c}_{su\omega t} - X^{c+}_{u\omega t}) \right. \quad \forall\, \omega \quad 5.21$$

$$+ \sum_{r,u,o,t} SP^{o}_{u\omega t}(X^{o}_{ru\omega t} - X^{o+}_{u\omega t})$$

$$+ \sum_{b,e,o,t} SP^{o}_{e\omega t}(X^{o}_{be\omega t} - X^{o+}_{e\omega t})$$

$$+ \sum_{b,d,o,t} SP^{o}_{d\omega t}(X^{o}_{bd\omega t} - X^{o+}_{d\omega t})$$

$$+ \sum_{a,u,g,t} SP^{g}_{u\omega t}\left(Y^{g}_{au\omega t} - Y^{g+}_{u\omega t}\right)$$

$$+ \sum_{a,d,g,t} SP^{g}_{d\omega t}\left(Y^{g}_{ad\omega t} - Y^{g+}_{d\omega t}\right)$$

$$+ \sum_{f,u,g,t} SP^{g}_{u\omega t}\left(Y^{g}_{fu\omega t} - Y^{g+}_{u\omega t}\right)$$

$$+ \sum_{f,d,g,t} SP^{g}_{d\omega t}\left(Y^{g}_{fd\omega t} - Y^{g+}_{d\omega t}\right)$$

$$\left. + \sum_{f,e,g,t} SP^{g}_{e\omega t}\left(Y^{g}_{fe\omega t} - Y^{g+}_{e\omega t}\right) \right]$$

$$\varphi r^{\omega} \geq 0 \qquad \forall\, \omega \quad 5.22$$

Similarly, Eq. (5.23) represents the difference between total cost per scenario and the auxiliary variable VaRc. If the total cost for any scenario is less than the $VaRc$, the φc^{ω} is inforced to equal to zero as defined in Eq. (5.23). However, if the total cost for any scenario is greater than the $VaRc$, the $\varphi c^{\omega}$is different from zero.

$$
\begin{aligned}
\varphi c^{\omega} \geq \sum_{t=1}^{T}(1+dr)^{-(t-1)} \Bigg\{ & \sum_{s,h,t} PC_{st}^{h} X_{st}^{h} + \sum_{a,n,t} PC_{at}^{n} Y_{at}^{n} \\
& + \Bigg[\sum_{s,r,c,t} SC_{srt}^{c}\, X_{sr\omega t}^{c} + \sum_{a,f,g,t} SC_{aft}^{g} Y_{af\omega t}^{g} + \sum_{s,u,c,t} CT_{sut}^{c} X_{su\omega t}^{c} \\
& + \sum_{s,r,c,t} CT_{srt}^{c} X_{sr\omega t}^{c} + \sum_{r,u,o,t} CT_{rut}^{o}\, X_{ru\omega t}^{o} + \sum_{r,b,o,t} CT_{rbt}^{o}\, X_{rb\omega t}^{o} \\
& + \sum_{b,e,o,t} CT_{bet}^{o}\, X_{be\omega t}^{o} + \sum_{b,d,o,t} CT_{bdt}^{o}\, X_{bd\omega t}^{o} + \sum_{k,u,o,t} CT_{kut}^{o}\, X_{ku\omega t}^{o} \\
& + \sum_{a,f,g,t} CT_{aft}^{g} Y_{af\omega t}^{g} + \sum_{a,u,g,t} CT_{aut}^{g} Y_{au\omega t}^{g} + \sum_{a,d,g,t} CT_{adt}^{g} Y_{ad\omega t}^{g} \\
& + \sum_{f,u,g,t} CT_{fut}^{g} Y_{fu\omega t}^{g} + \sum_{f,d,g,t} CT_{fdt}^{g} Y_{fd\omega t}^{g} + \sum_{f,u,g,t} CT_{fut}^{g} Y_{fu\omega t}^{g} \\
& + \sum_{f,e,g,t} CT_{fet}^{g} Y_{fe\omega t}^{g} + \sum_{k,u,g,t} CT_{kut}^{g} Y_{ku\omega t}^{g} + \sum_{k,u,o,t} IC_{kt}^{o}\, X_{ku\omega t}^{o} \\
& + \sum_{k,u,g,t} IC_{kt}^{g} Y_{ku\omega t}^{g} + \sum_{s,h,t} HC_{st}^{h}\, X_{st}^{h+} + \sum_{a,n,t} HC_{at}^{n}\, Y_{at}^{n+} \\
& + \sum_{r,c,t} HC_{rt}^{c}\, X_{rt}^{c+} + \sum_{b,o,t} HC_{bt}^{o}\,,\, X_{b\omega t}^{o+} + \sum_{f,g,t} HC_{ft}^{g}\, Y_{f\omega t}^{g+} \\
& + \sum_{e,o,t} (w_{et}^{o+} X_{e\omega t}^{o+} + w_{et}^{o-} X_{e\omega t}^{o-}) + \sum_{d,o,t} (w_{dt}^{o+} X_{d\omega t}^{o+} + w_{dt}^{o-} X_{d\omega t}^{o-}) \\
& + \sum_{u,o,t} (w_{ut}^{o+} X_{u\omega t}^{o+} + w_{ut}^{o-} X_{u\omega t}^{o-}) + \sum_{e,g,t} \left(w_{et}^{g+} Y_{e\omega t}^{g+} + w_{et}^{g-} Y_{e\omega t}^{g-}\right) \qquad \forall\, \omega \\
& + \sum_{d,g,t} \left(w_{dt}^{g+} Y_{d\omega t}^{g+} + w_{dt}^{g-} Y_{d\omega t}^{g-}\right) + \sum_{u,g,t} \left(w_{ut}^{g+} Y_{u\omega t}^{g+} + w_{ut}^{g-} Y_{u\omega t}^{g-}\right) \\
& + \sum_{u,c,t} (w_{ut}^{c+} X_{u\omega t}^{c+} + w_{ut}^{c-} X_{u\omega t}^{c-}) \Bigg] \Bigg\} - VaRc
\end{aligned}
\qquad 5.23
$$

$$
\varphi c^{\omega} \geq 0 \qquad \forall\, \omega \qquad 5.24
$$

5.3.3 MOR Model Objective Functions

The total cost objective function is modified by adding a term representing a CVaR. A weighting value is injected to materialize the tradeoff between total cost and risk aversion.

Based on *CVaR* definition Eq.5.14 and Eq.**Error! Reference source not found.** formulates total cost and revenue objective functions as proposed by Rockafellar and Uryasev (2000). The utilized formulation of CVaR is an acceptable approximation used in case of discrete distribution (i.e., representing uncertainty as a finite number of scenarios), (Rockafellar and Uryasev, 2000; Rockafellar and Uryasev, 2002; Sarykalin et al., 2008).

$$
\begin{aligned}
\text{Minimize } f_1 = (1 & \\
-\beta) & \left[\sum_{t=1}^{T}(1+dr)^{-(t-1)}\left\{\sum_{s,h,t} PC_{st}^{h} X_{st}^{h} + \sum_{a,n,t} PC_{at}^{n} Y_{at}^{n}\right.\right. \\
& + \sum_{\omega\in\Omega}\pi_\omega\left[\sum_{s,r,c,t} SC_{srt}^{c}\, X_{sr\omega t}^{c} + \sum_{a,f,g,t} SC_{aft}^{g} Y_{af\omega t}^{g} + \sum_{s,u,c,t} CT_{sut}^{c} X_{su\omega t}^{c}\right. \\
& + \sum_{s,r,c,t} CT_{srt}^{c} X_{sr\omega t}^{c} + \sum_{r,u,o,t} CT_{rut}^{o}\, X_{ru\omega t}^{o} + \sum_{r,b,o,t} CT_{rbt}^{o}\, X_{rb\omega t}^{o} \\
& + \sum_{b,e,o,t} CT_{bet}^{o}\, X_{be\omega t}^{o} + \sum_{b,d,o,t} CT_{bdt}^{o}\, X_{bd\omega t}^{o} + \sum_{k,u,o,t} CT_{kut}^{o}\, X_{ku\omega t}^{o} \\
& + \sum_{a,f,g,t} CT_{aft}^{g} Y_{af\omega t}^{g} + \sum_{a,u,g,t} CT_{aut}^{g} Y_{au\omega t}^{g} + \sum_{a,d,g,t} CT_{adt}^{g} Y_{ad\omega t}^{g} \\
& + \sum_{f,u,g,t} CT_{fut}^{g} Y_{fu\omega t}^{g} + \sum_{f,d,g,t} CT_{fdt}^{g} Y_{fd\omega t}^{g} + \sum_{f,u,g,t} CT_{fut}^{g} Y_{fu\omega t}^{g} \\
& + \sum_{f,e,g,t} CT_{fet}^{g} Y_{fe\omega t}^{g} + \sum_{k,u,g,t} CT_{kut}^{g} Y_{ku\omega t}^{g} + \sum_{k,u,o,t} IC_{kt}^{o}\, X_{ku\omega t}^{o} \\
& + \sum_{k,u,g,t} IC_{kt}^{g} Y_{ku\omega t}^{g} + \sum_{s,h,t} HC_{st}^{h}\, X_{st}^{h+} + \sum_{a,n,t} HC_{at}^{n}\, Y_{at}^{n+} + \sum_{r,c,t} HC_{rt}^{c}\, X_{rt}^{c+} \\
& + \sum_{b,o,t} HC_{bt}^{o}\,,\, X_{b\omega t}^{o+} + \sum_{f,g,t} HC_{ft}^{g}\, Y_{f\omega t}^{g+} + \sum_{e,o,t}(w_{et}^{o+} X_{e\omega t}^{o+} + w_{et}^{o-} X_{e\omega t}^{o-}) \\
& + \sum_{d,o,t}(w_{dt}^{o+} X_{d\omega t}^{o+} + w_{dt}^{o-} X_{d\omega t}^{o-}) + \sum_{u,o,t}(w_{ut}^{o+} X_{u\omega t}^{o+} + w_{ut}^{o-} X_{u\omega t}^{o-}) \\
& + \sum_{e,g,t}\left(w_{et}^{g+} Y_{e\omega t}^{g+} + w_{et}^{g-} Y_{e\omega t}^{g-}\right) + \sum_{d,g,t}\left(w_{dt}^{g+} Y_{d\omega t}^{g+} + w_{dt}^{g-} Y_{d\omega t}^{g-}\right) \\
& \left.\left.\left. + \sum_{u,g,t}\left(w_{ut}^{g+} Y_{u\omega t}^{g+} + w_{ut}^{g-} Y_{u\omega t}^{g-}\right) + \sum_{u,c,t}(w_{ut}^{c+} X_{u\omega t}^{c+} + w_{ut}^{c-} X_{u\omega t}^{c-})\right]\right\}\right] \\
& + \beta\left[VaRc + \frac{1}{1-\alpha}\sum_{\omega\in\Omega}\pi_\omega \varphi c^{\omega}\right]
\end{aligned}
$$

The total revenue objective function is modified by adding a term representing a CVaR.

$$
\begin{aligned}
Maximize \;\; f_2 = (1 &\\
- \beta)\Bigg[\sum_{t=1}^{T} (1+dr)^{-(t-1)} \sum_{\boldsymbol{\omega}\in\boldsymbol{\Omega}} \pi_\omega \Bigg[&\sum_{s,u,c,t} SP^{c}_{u\omega t}(X^{c}_{su\omega t} - X^{c+}_{u\omega t}) \\
&+ \sum_{r,u,o,t} SP^{o}_{u\omega t}(X^{o}_{ru\omega t} - X^{o+}_{u\omega t}) + \sum_{b,e,o,t} SP^{o}_{e\omega t}(X^{o}_{be\omega t} - X^{o+}_{e\omega t}) \\
&+ \sum_{b,d,o,t} SP^{o}_{d\omega t}(X^{o}_{bd\omega t} - X^{o+}_{d\omega t}) + \sum_{a,u,g,t} SP^{g}_{u\omega t}\left(Y^{g}_{au\omega t} - Y^{g+}_{u\omega t}\right) \\
&+ \sum_{a,d,g,t} SP^{g}_{d\omega t}\left(Y^{g}_{ad\omega t} - Y^{g+}_{d\omega t}\right) + \sum_{f,u,g,t} SP^{g}_{u\omega t}\left(Y^{g}_{fu\omega t} - Y^{g+}_{u\omega t}\right) \\
&+ \sum_{f,d,g,t} SP^{g}_{d\omega t}\left(Y^{g}_{fd\omega t} - Y^{g+}_{d\omega t}\right) + \sum_{f,e,g,t} SP^{g}_{e\omega t}\left(Y^{g}_{fe\omega t} - Y^{g+}_{e\omega t}\right) \Bigg]\Bigg] \\
&+ \beta \left[VaRr - \frac{1}{1-\alpha} \sum_{\omega\in\Omega} \pi_\omega \varphi r^{\omega} \right]
\end{aligned}
$$

The service level objective function remains the same.

5.4 Applied Case Study: MOR Model

The MOR model is verified and validated using the Kingdom of Saudi Arabia HCSC stated in section 3.3. For the purpose of solving the MOR model, a risk level of 0.5 is assumed to materialize the tradeoff between economic goals and risk term. In addition, to ensure that the expected value of scenarios having low revenue (or high cost) lay within the 20.01% quantile of the revenue (or cost) distribution.

5.4.1 Results and Discussion of MOR Model

The MOR model is solved using the augmented ε-constraint method under the same conditions that have been used for solving the MOS model after modifying the GAMS code to include objective functions and risk constraints. The statistics of MOR model are illustrated in Table 5.2.

Table 5.2 MOR model statistics

Blocks of Equations	94	Single Equations	15072
Blocks of Variables	55	Single Variables	24908
CPU time (s)	3690	Non zero Elements	122266

The payoff matrix obtained by lexicographic optimization are summarized in Table 5.3.

Table 5.3 Payoff matrix of the MOR model

	Total cost ($ M/3 months)	Total revenue ($ M/3 months)	Service level
Minimize total cost	7767	37097	0.875
Maximize total revenue	8679	37290	0.944
Maximize service level	7804	37156	0.934

Clearly from Fig. 5.2, Pareto-optima surface of the MOR model has the same shape of one that produced from the MOS and MOD models. For the purpose of clarifying and comparison, TOPSIS with equally weighted for the three objectives are utilized.

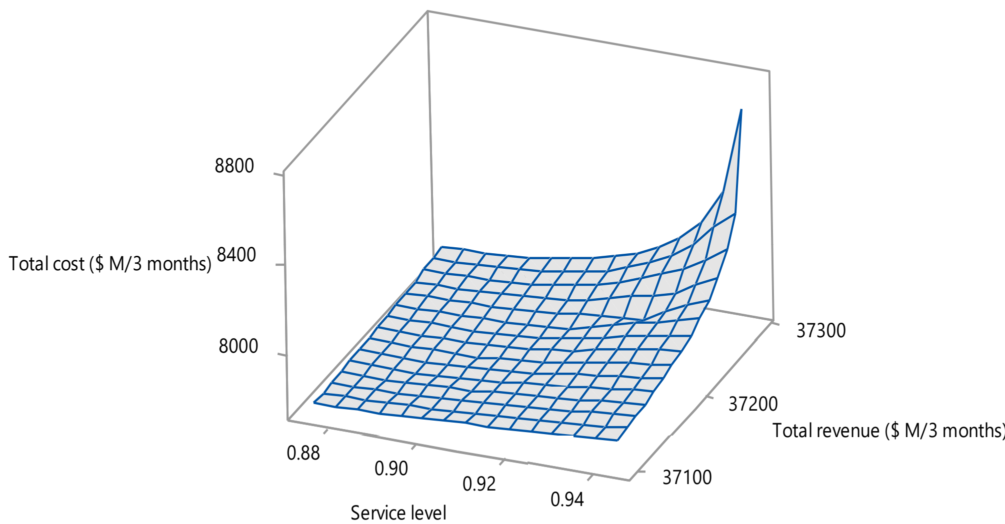


Figure 5.2 3D Pareto curve for MOR model

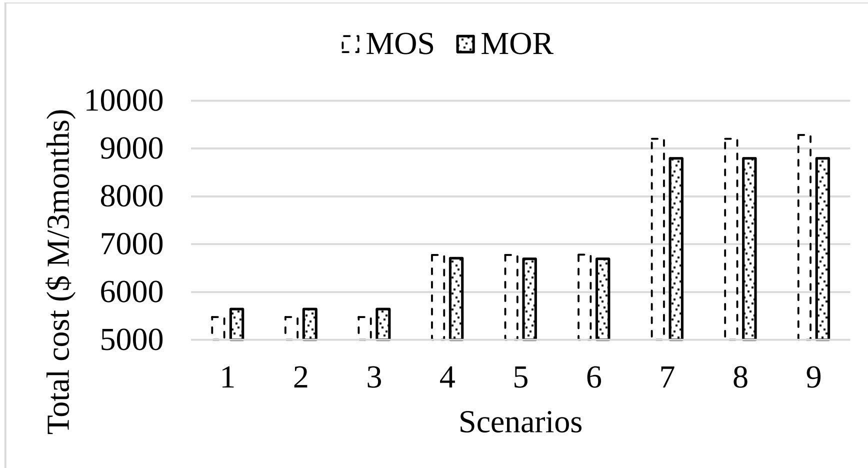
The preferred tactical plan from the MOR model is listed in Table 5.4. Comparing this plan with the plan obtained by the MOS model case (Table 4.6) regarding total cost, total revenue, service level, oil and gas processing, and imports, the MOR model experiences higher total cost and lower total revenue, hence lower profit. The reason behind this trend is that in the MOR model, risk constraints are added to the feasible region which leads to reduction in the feasible region. Accordingly, total cost increases, while total revenue decreases.

Table 5.4 Preferred plan from the MOR model

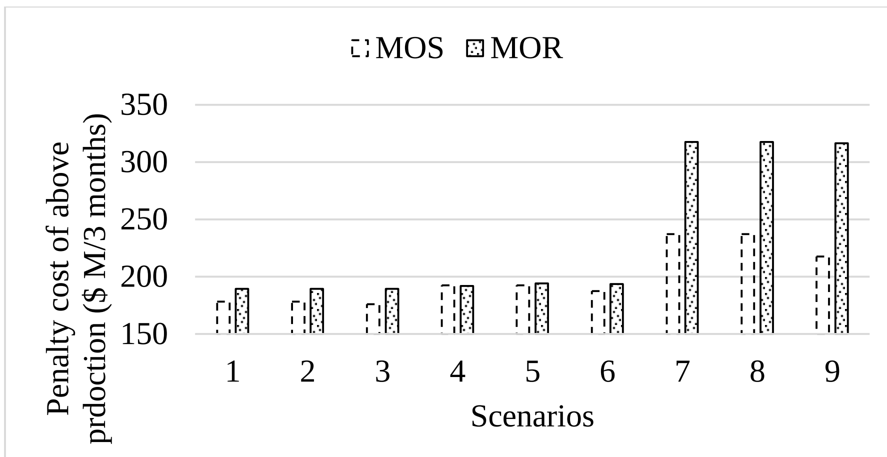
Total cost =	$ 7876 M /3 months	Oil refining =	2.802 MBL/day
Revenue =	$ 37238 M /3 months	Oil imports =	0.309 MBL/day
Service level =	0.931	Gas imports =	255 Mscft/day
Oil processing =	10.29 MBL/day	Gas fractioning	1978 Mscft/day

The MOR model shows higher service level values than the MOS model because the MOR model records higher values for local oil and gas processing to overcome the shortages and then avoiding the higher penalty of producing under demand especially in scenarios of high demands as shown in Fig 5.3 (c).

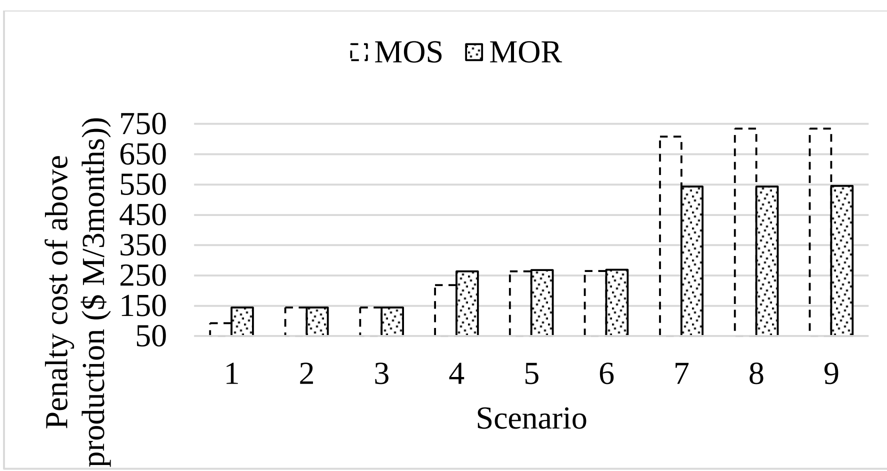
The total cost and penalty cost of productions above and below demands for the MOS and MOR models are shown in Fig. 5.3. In the scenarios of base and high demands, the MOR model shows lower costs than the MOS model since the purpose of the MOR model is to reduce the risk of exceeding cost greater than target in any scenario. With the same line, in the last three scenarios (7,8,9) of high demands, the MOR model reduces below penalty cost by satisfying the demand from local production. Hence, the MOR model attained its purpose by reducing the risk of facing a high cost in any the scenario.



(a) Total cost



(b) Penalty cost of production above demands



(c) Penalty cost of production below demands

Figure 5.3 Variation of cost elements with scenarios for MOS and MOR models

The profit obtained from the three proposed models are shown in Fig. 5.4. The MOR model is more profitable than the MOS model in most of scenarios especially the scenarios that have base and high demands (4,5,6,7,8, and 9) because in the MOR model, most of the demand are satisfied from local production. Hence, the penalty cost of below production is reduced which leads to low total cost and then high profit. The obtained results prove the main purpose of risk measures; CVaR; to reduce the probability of experiencing in scenarios that give low return.

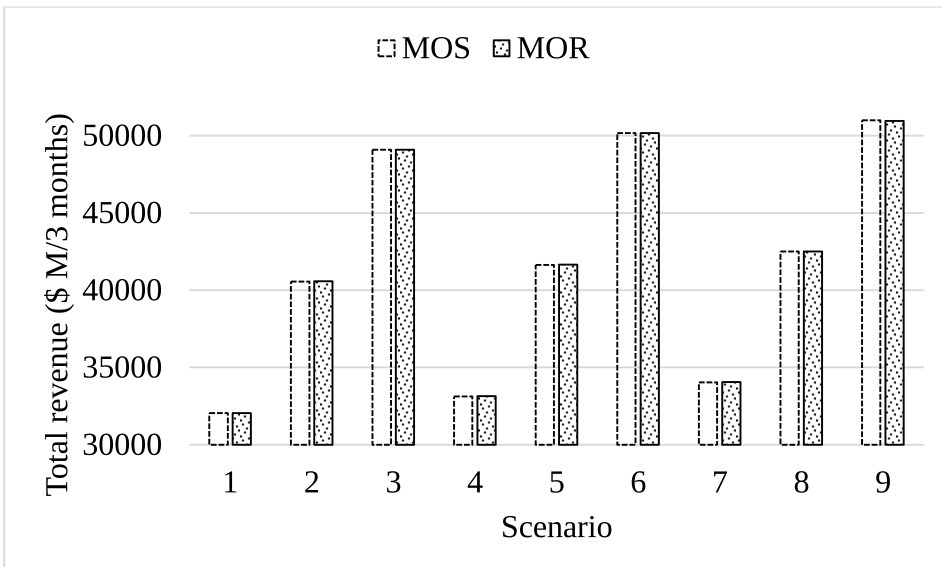
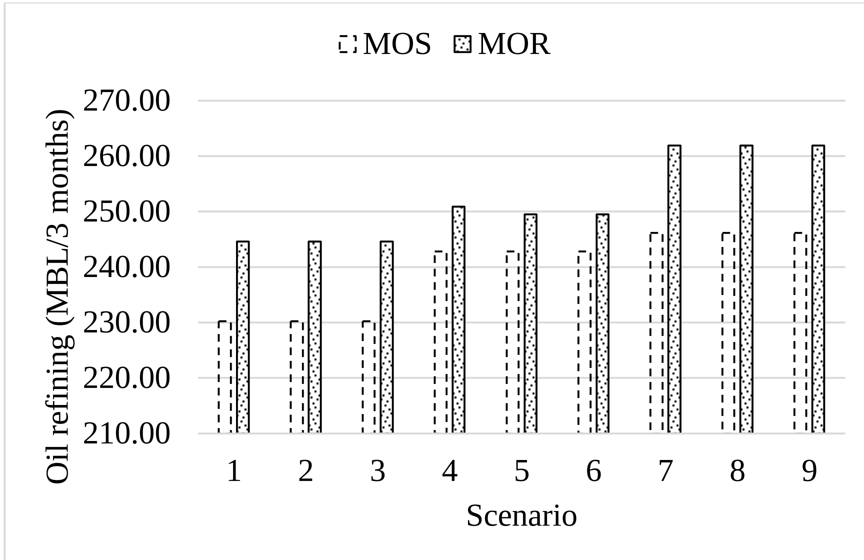
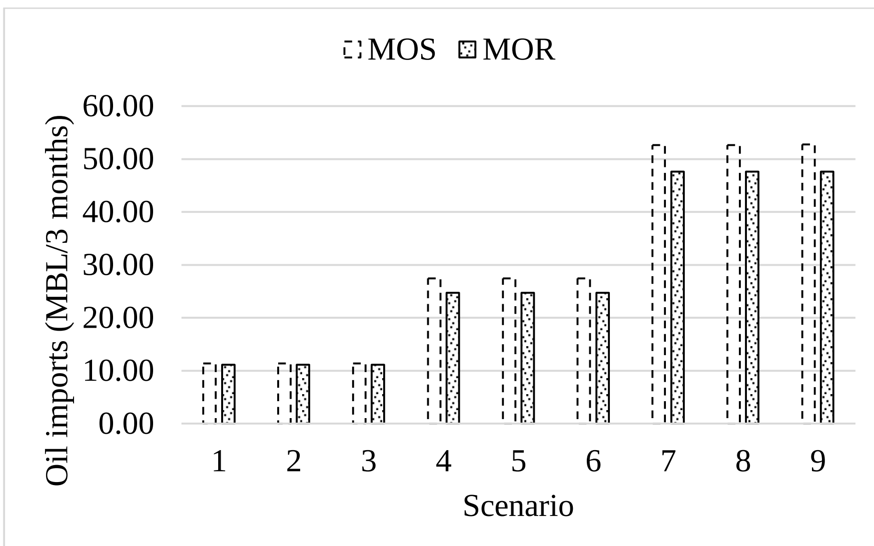


Figure 5.4 Total revenue with respect to each scenario for MOS and MOR models

The local refining and oil imports for the MOS and MOR models are shown in Fig. 5.5. The MOR model shows plans with high local refining and lower imports than the MOS model in all of the scenarios in order to avoid high penalty costs of production below demands. On the other hand, the MOS model results in high oil imports to overcome shortages in demands.



(a) Local oil refining



(b) Oil imports

Figure 5.5 Oil refining and imports versus scenarios for MOS and MOR models

The optimal values of VaR, CVaR,, $\varphi c^{\omega} a$nd φr^{ω}per scenario are provided in Table 5.5. We observe that $\varphi r^{\omega}$are different from zero in scenario 1 and scenario 4 because the value of revenue in these scenarios are less than the target VaR ($ 34056 M/3 months) by $ 1999 M /3months and $ 903 M /3 months, respectively. Therefore, scenario 1 and 4 are the worst scenarios regarding total revenue. The expected value of revenues in these scenarios; CVaR is equal to $ 32867 M/3 months. Based on the selected risk level and confidence level concluded that Kingdom of Saudi Arabia could face a risk (revenue lower than specific value VaR) if scenarios of low prices happened with low and base demands because the low prices lead to low cash flow.

Regarding cost, the variable φc^{ω} is equal to zero in all scenarios except scenario 9. The expected cost value of scenarios greater than the target VaR is CVaR=to $ 8792 M/3 months. This means that under the selected values of risk level (β) and risk confidence level (α), Kingdom of Saudi Arabia will not face exceeding in budget because it has sufficient resources and the cost of producing oil and gas products is low compared to other countries.

Table 5.5 Optimal results of risk variables ($ M/3 months).

Objective function	VaR	CVaR	Risk value per scenario (φr^{ω} & φc^{ω})								
			1	2	3	4	5	6	7	8	9
Revenue	34056	32867	1999	0	0	903	0	0	0	0	0
Cost	8793	8792	0	0	0	0	0	0	0	0	1

Table 5.6 shows the total cost for both MOS and MOR models and the optimal value of VaR (target of total cost). Before incorporating the CVaR into the stochastic model, three scenarios (7,8, and 9) records costs higher than the target, VaR. While, after incorporating the CVaR, the total costs of most scenarios improved and only one scenario (9) has total cost greater than the target, VaR by $ 1 M/ 3 months.

Table 5.6 Total cost for MOS and MOR models ($ M/3 months).

Scenario / Model	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
MOS	5476	5476	5480	6774	6774	6782	**9200**	**9200**	**9282**
MOR	5647	5647	5647	6705	6697	6697	8792	8792	8793
VaRc	8792								

Table 5.7 shows the total revenue for both MOS and MOR models and the optimal value of VaR (target of total revenue). Before incorporating the CVaR into the stochastic model, three scenarios (1,4, and 7) records revenues lower than the target, VaR. While, after incorporating the CVaR, the total revenue of most scenarios improved and two scenarios (1,4) have total revenue less than the target, VaR by $ 2004 and $ 911 M/ 3 months, respectively.

Table 5.7 Total revenue for MOS and MOR models ($ M/3 months).

Scenario / Model	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
MOS	32043	40552	49096	33130	41626	50158	34040	42507	50987
MOR	32052	40576	49100	33145	41651	50176	34056	42501	50961
VaRc	34056								

Fig. 5.6 and Fig. 5.7 represent the cumulative probability distribution functions for both total revenue and total cost, respectively. The expected value of total revenue and total costs are $ 37238 M/ 3 months and $ 7876 M/ 3 months, respectively. From Fig. 5.6, we

confident with 80 % that the expected value of scenarios having low revenue (lower than VaR= $ 34056 M/ 3 months) lay within the 20% quantile of the revenue distribution.

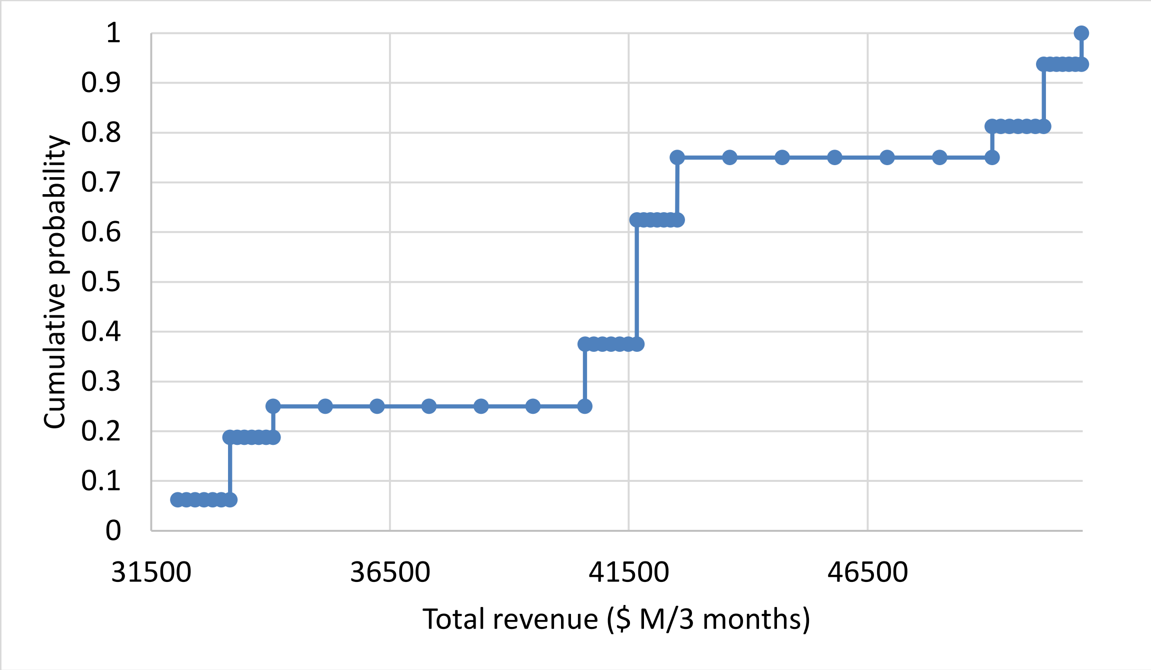


Figure 5.6 Cumulative probability distribution of total revenue.

From Fig. 5.8, we confident with 80 % that the expected value of scenarios having high cost (greater than VaR= $ 8792 M/ 3 months) lay within the 20% quantile of the cost distribution.

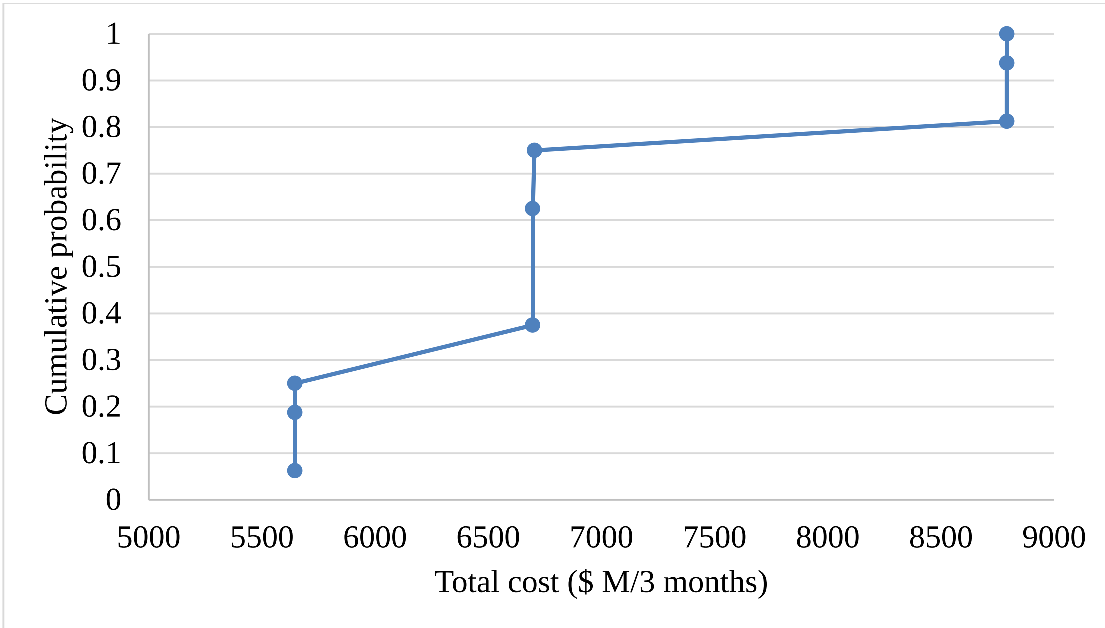


Figure 5.7 Cumulative probability distribution of total cost.

5.4.2 Sensitivity Analysis of MOR Model

The effect of changing risk level (β) and risk confidence level (α) on the total revenue, total cost, and CVaR of revenue and cost are conducted in this section. First, the variations of the CVaR with total revenue are plotted at different values of risk level that could be accepted by decision maker (weighting the tradeoffs between risk and revenue) at constant value of risk confidence level.

Fig. 5.8 shows the tradeoffs between CVaR and total revenue at different values of risk level. As risk level increases, this means that the revenue term becomes less significant with respect to the risk term. In other words, the decision maker is risk averse. Thus, the CVaR (the expected value of scenarios greater than target VaR) is maximized over expected revenue. For $\beta = 0$, the risk term in the objective function is neglected and the resulting problem becomes the risk neutral one; MOS model.

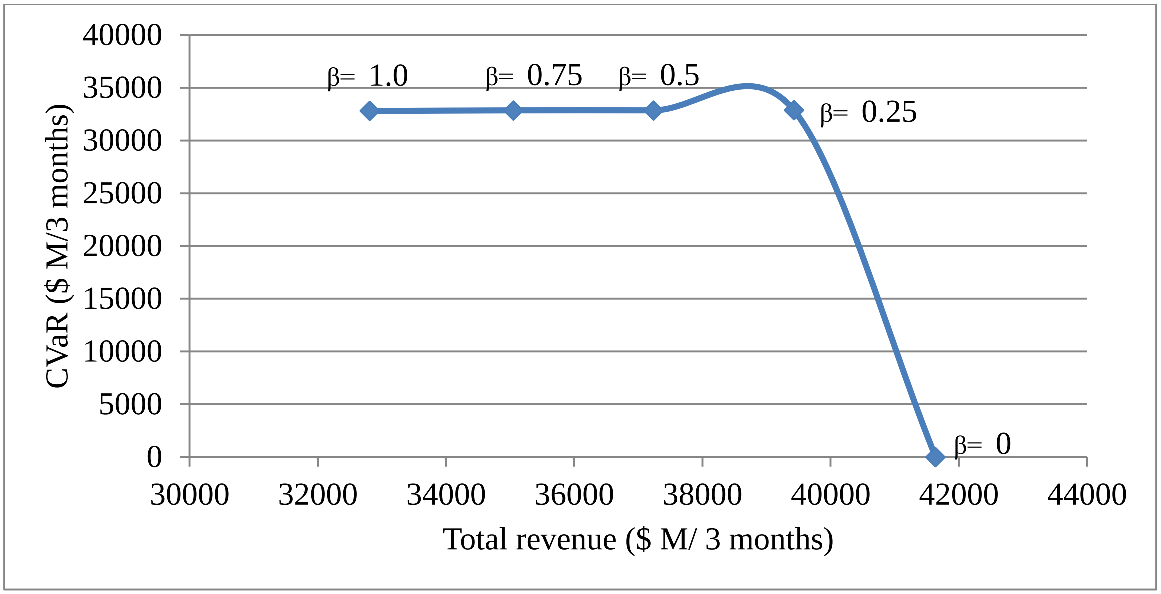


Figure 5.8 CVaR versus total revenue at different values of risk level

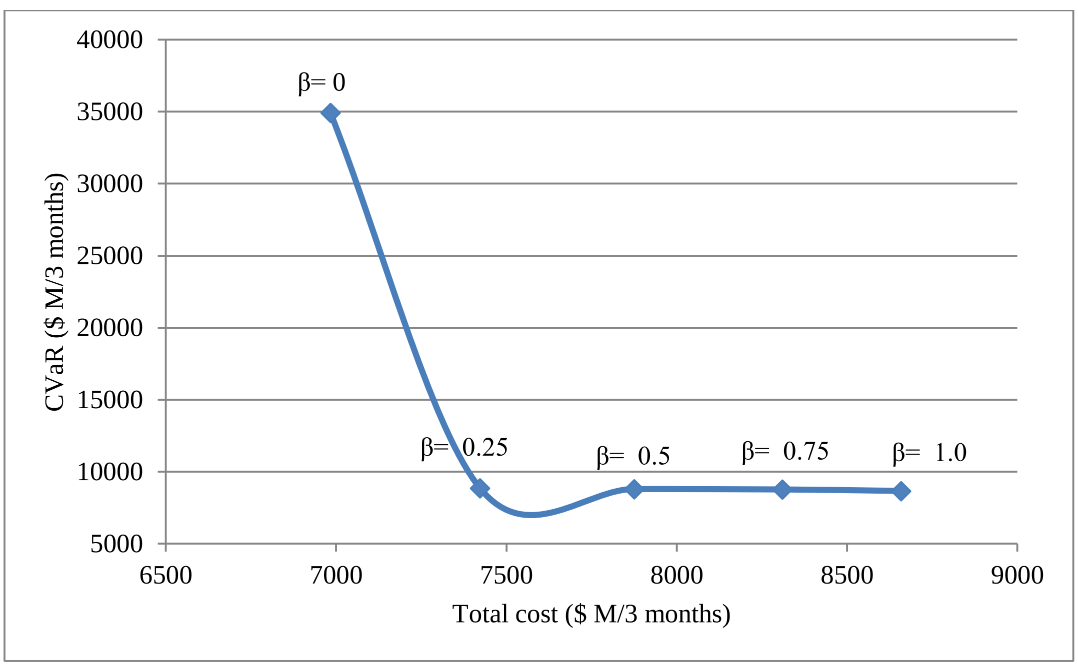


Figure 5.9 CVaR versus total cost at different values of risk level

Fig. 5.9 shows the trade-offs between CVaR and total cost at different values of risk level. As risk level increases, this means that the expected cost term becomes less significant with respect to the risk term. In other words, the decision maker is risk averse. Thus, the CVaR is minimized over total cost. For $\beta = 0$, the risk term in the objective function is neglected and the resulting problem becomes risk neutral one; MOS model.

The effects of risk confident level (α) on the target of total revenue and total cost are investigated. The risk confident level is provided to ensure that the expected values of scenarios having low revenues (or high costs) lay within the (1- α) % quantile of the revenue (or costs). From Fig. 5.10, as α increases target of revenue; VaR decreases. Increasing α; means reducing area under the quantile of revenue distribution curve (1- α) which leads to a smaller targets of revenue that could be accepted by the decision maker.

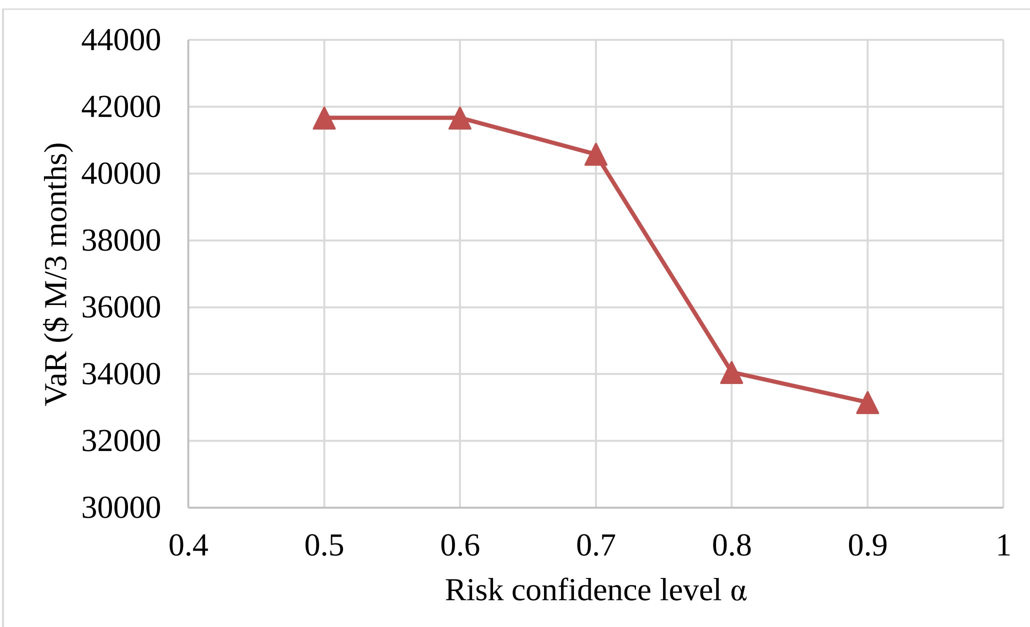


Figure 5.10 Effect of risk confidence level on revenue target

On the other hand, Fig. 5.11 shows the effect of α on target of cost; VaR. As α increases, target of cost increases. Increasing α; means reducing area under the quantile of cost distribution curve (1- α), leads to a higher targets of cost that could be accepted by the decision maker. As a main conclusion, as α increases the decision maker is risk taker.

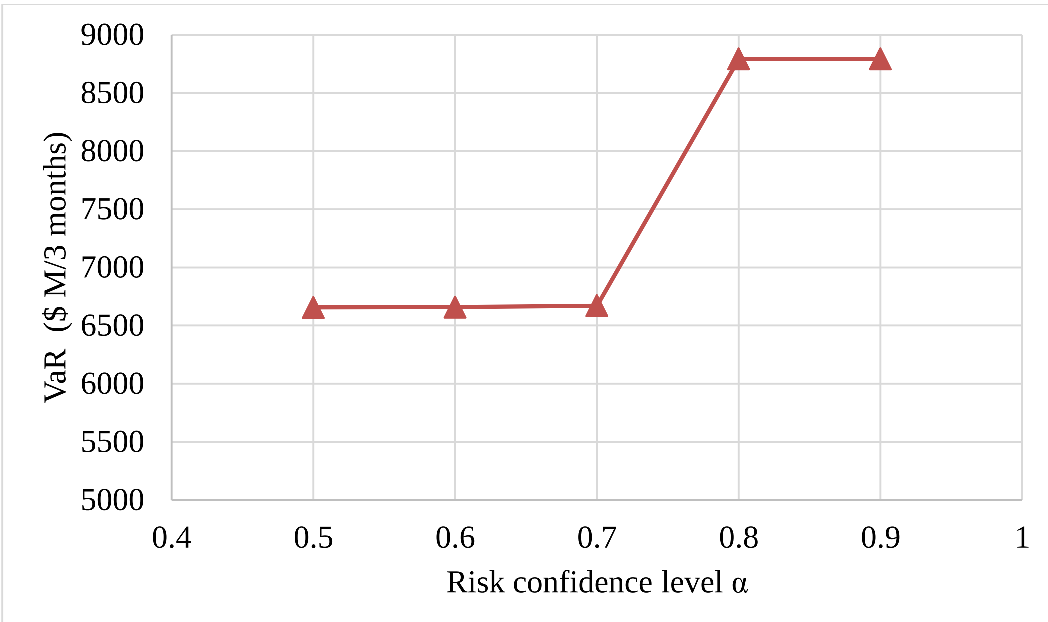


Figure 5.11 Effect of risk confidence level on cost target

The effect of risk level on total revenue and revenue target is studied at different values of risk confidence level as shown in Fig. 5.12 and Fig. 5.13. As risk level increases, expected revenue decreases because more weight is assigned for mitigating risk over maximizing revenue for all values of risk confidence level. For example, if Kingdom of Saudi Arabia gives high weight for risk and at the same time ensures that most of scenarios give revenue greater than the target VaR; point B (β=1 and α=0.25), the expected revenue will be ($ 38800 M/3 months) less than target ($ 41677 M/3 months) (maximum risk aversion point).

This plan shows that scenarios (1,2,4,5 and 7) will yield a revenue less than the target revenue by ($ 10557 M/3 months, $ 2030 M/3 months, $ 9463 M/3 months, and $ 85051 M/3 months, respectively, as shown in Table 5.8.

On the other hand, if Kingdom of Saudi Arabia gives low weight for risk; point A (β=0 and α=0.95), the expected revenue will be ($ 42000 M/ 3months) greater than target VaR ($0 M/3 months) (maximum risk taking point). This plan shows that all scenarios will yield a revenue greater than the target value as shown in Table 5.8.

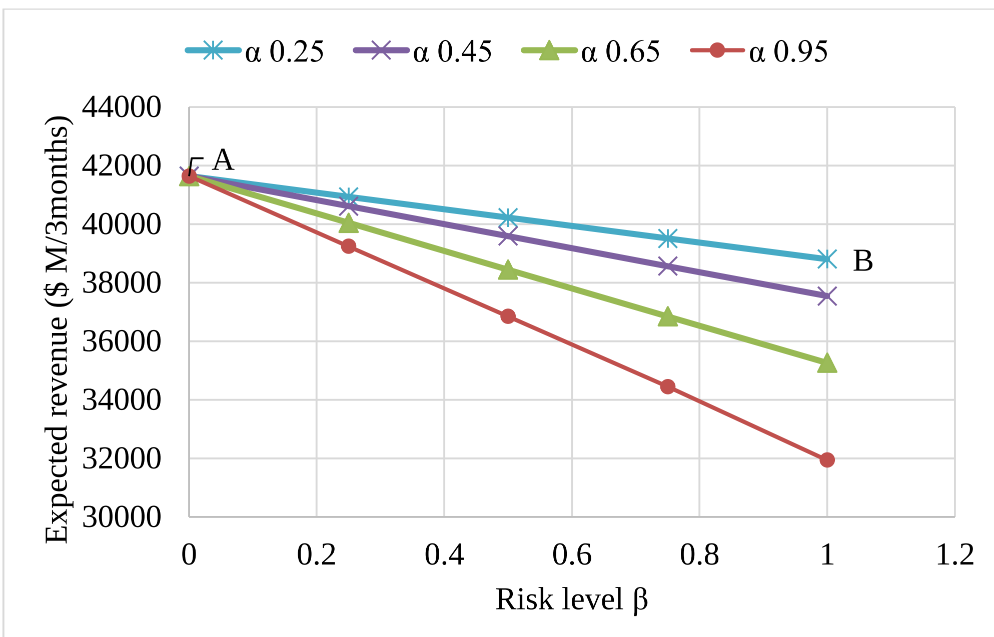


Figure 5.12 Effect of risk level and risk confidence level on expected revenue

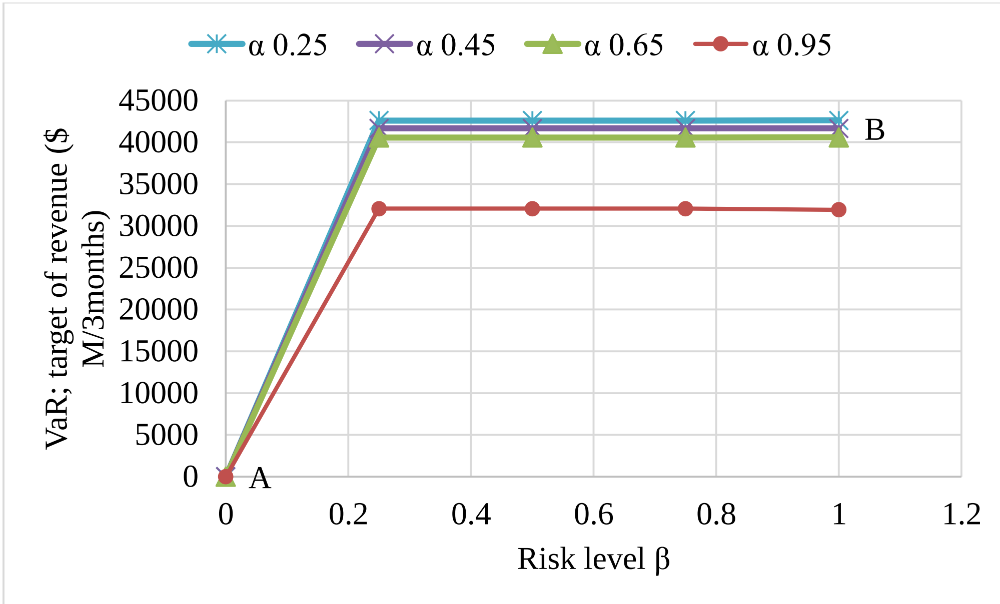


Figure 5.13 Effect of risk level and risk confidence level on revenue target

Table 5.8 Risk variables φr^{ω} of revenue

α	**Scenario** / **β**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0.95	0	0	0	0	0	0	0	0	0	0
	0.25	0	0	0	0	0	0	0	0	0
	0.5	0	0	0	0	0	0	0	0	0
	0.75	0	0	0	0	0	0	0	0	0
	1	0	0	0	0	0	0	0	0	0
0.65	0	0	0	0	0	0	0	0	0	0
	0.25	8527	0	0	7432	0	0	6477	0	0
	0.5	8527	0	0	7431	0	0	6475	0	0
	0.75	8527	0	0	7432	0	0	6473	0	0
	1	8528	0	0	7433	0	0	6473	0	0
0.45	0	0	0	0	0	0	0	0	0	0
	0.25	9612	1086	0	8523	0	0	7564	0	0
	0.5	9613	1087	0	8518	0	0	7563	0	0
	0.75	9613	1086	0	8519	0	0	7561	0	0
	1	9615	1087	0	8519	0	0	7562	0	0
0.25	0	0	0	0	0	0	0	0	0	0
	0.25	10558	2028	0	9465	942	0	8505	0	0
	0.5	10554	2028	0	9464	941	0	8504	0	0
	0.75	10554	2027	0	9461	941	0	8503	0	0
	1	10557	2030	0	9463	944	0	8505	0	0

The effect of risk level on expected cost and target cost is studied at different values of risk confidence level as shown in Fig. 5.14 and Fig. 5.15. As risk level increases, expected cost increases because more weight is assigned for mitigating risk over minimizing cost for all values of risk confidence level. If Kingdom of Saudi Arabia gives high weight for risk and at the same time ensures that most of scenarios give cost smaller than the target VaR; point B (β=1 and α=0.25), the cost will be ($ 7451 M/3 months) greater than target VaR ($ 7451 M/3 months). This plan shows that scenarios (4,5,7,8 and 9) will yields a costs greater than the target value as shown in Table 5.9.

If Kingdom of Saudi Arabia gives low weight for risk VaR; point A (β=0 and α=0.95), the cost will be ($ 6976 M/3months) less than target VaR ($ 0 M/3 months). This plan shows that all scenarios will yields a cost greater than the target value by as shown in Table 5.9.

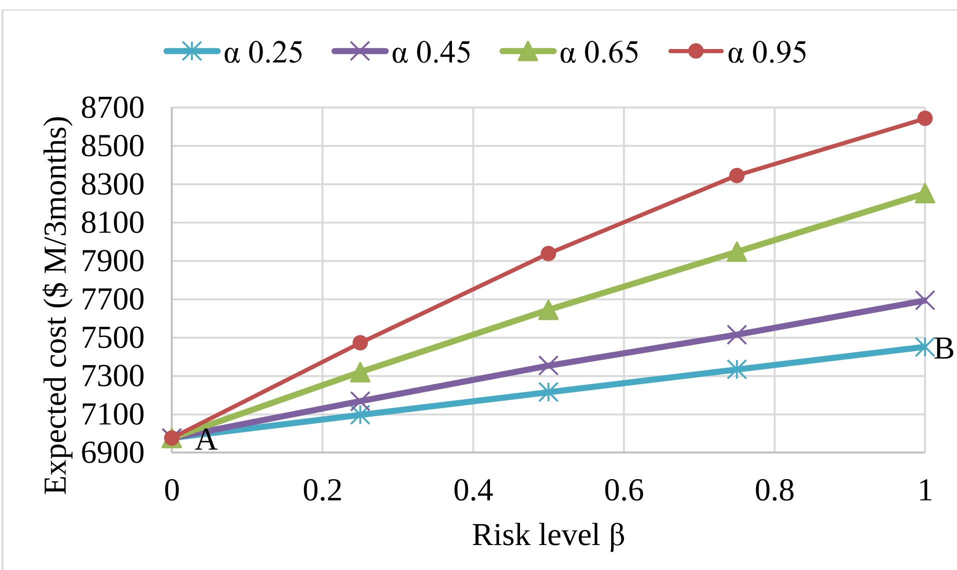


Figure 5.14 Effect of risk level and risk confidence level on expected cost

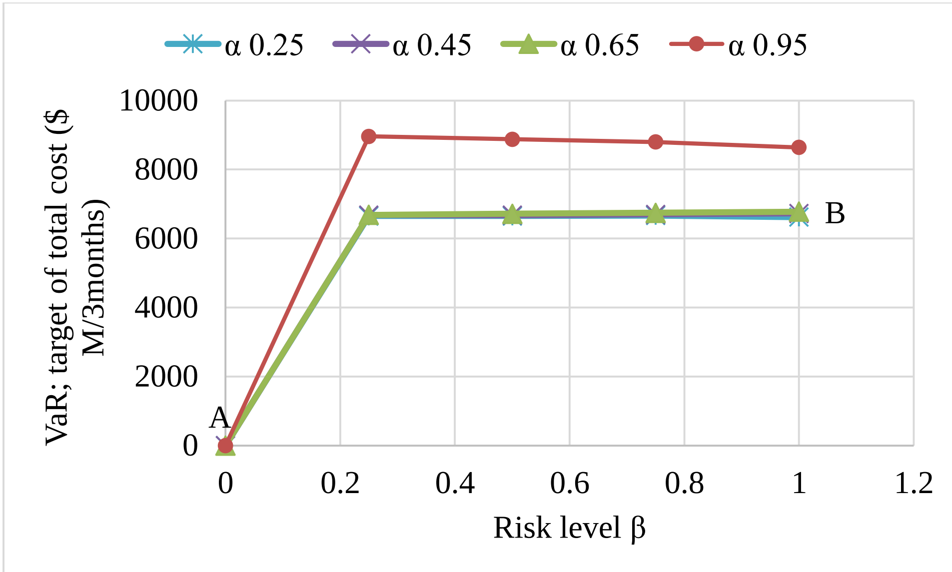


Figure 5.15 Effect of risk level and risk confidence level on cost target

Table 5.9 Risk variables $\boldsymbol{\varphi c^{\omega}}$ of cost.

α	**Scenario** / **β**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0.95	0	5505	5535	5535	6660	6688	6688	8999	9020	9020
	0.25	0	0	0	0	0	0	0	0	0
	0.5	0	0	0	0	0	0	0	0	0
	0.75	0	0	0	0	0	0	0	0	0
	1	0	0	0	0	0	0	0	0	0
0.65	0	5505	5535	5535	6660	6688	6688	8999	9020	9020
	0.25	0	0	0	0	0	0	2299	2308	2316
	0.5	0	0	0	0	0	0	2279	2165	2285
	0.75	0	0	0	0	0	0	2242	2089	2103
	1	0	0	0	0	0	0	2244	2008	2008
0.45	0	5505	5535	5535	6660	6688	6688	8999	9021	9021
	0.25	0	0	0	0	0.004	0	2315	2333	2333
	0.5	0	0	0	0	0	0	2313	2314	2329
	0.75	0	0	0	0	0	0	2304	2153	2177
	1	0	0	0	0	0	0	2300	2068	2068
0.25	0	55045	5535	5535	6660	6688	6688	8999	9021	9021
	0.25	0	0	0	0	27.82	27.82	2344	2361	2361
	0.5	0	0	0	0	27.82	27.82	2343	2359	2359
	0.75	0	0	0	0	11.28	11.27	2335	2342	2338
	1	0	0	0	87.71	87.71	0	2405	2419	2193

From the above figures, it is clear that the risk level does not have effect on the optimal targets of the revenue and cost for all values of risk confidence level.

5.5 Conclusion

In this chapter, the stochastic model formulated in chapter 4 was extended to incorporate the risk of uncertainty and to consider financial risks in addition to economic goals. The developed model is a multi-objective risk (MOR) model for midterm tactical planning of an integrated oil and gas supply chain. The risk is controlled and mitigated through utilizing a coherent risk measure; CVaR. The proposed MOR model helps in assessing the trade-off among financial risks and economic goals of HCSC. In general, it is concluded that including risk measure in modeling of stochastic programming have great impact on total cost, total revenue, service level, and all the tactical decisions of the HCSC.

The plan obtained by the MOR model are compared with plan obtained by the MOS model, and MOD model. The MOR model shows higher values of local oil and gas processing to avoid high cost of producing under demand which prove the purpose of using risk model. A sensitivity analysis was conducted on the MOR model under different values of risk parameters. if Kingdom of Saudi Arabia is risk taker, Kingdom of Saudi Arabia should select its plan based on (β=0 and α= 0.95). Oppositely, if the Kingdom of Saudi Arabia is risk seeker, Kingdom of Saudi Arabia should select its plan based on (β=1 and α=0.25). The specific limitations of the prosed model are: (1) the assumption of α and β values where the risk attitude level of the decision maker is not known, and (2) the approximation of CVaR equation used for continuous distribution to be applied to a discrete distribution. As conclusion, there is a trade-off between risk level and risk conference level and the difficulty of CVaR risk measure in practical situations is to consider suitable values for the risk level (β) and risk confidence level (α). It is up to decision maker to choose the level of risk he/she is willing to face and the degree of confident.

CHAPTER 6

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

6.1 Summary

Each chapter of this dissertation has a separate conclusion. Accordingly, in this section, the major finding of the dissertation will be summarized at a high level. This dissertation considered the formulation of an integrated tactical multi-objective optimization model for downstream oil and gas supply chain in certain and uncertain market conditions with and without considering risk or decision maker preference. Chapter 1 introduced the concept of HCSC, stated the problem under study, and outlined dissertation objectives and motivation. Chapter 2 provided a comprehensive literature review focusing on two categories; deterministic and stochastic models.

Chapters 3 presents the multi-objective deterministic model. The objectives of the models are: total cost, total revenue, and service level. A case study from Saudi Arabia HCSC is described. The results of the MOD model were discussed to demonstrate utility of the model. A sensitivity analysis was performed to study the impact of prices and demand on the model results. The MOD model is extended to address uncertainty in chapter 4. The proposed model is a multi-objective stochastic programming model. The MOS model was solved and the results were discussed and compared with the results of the MOD model. A sensitivity analysis on the parameters of the MOS model was conducted with focus on price and demand.

In chapter 5 of the dissertation, the MOS model has been extended by incorporating the risk of uncertainties using CVaR as a risk measure. The proposed model is a multi-objective risk model (MOR). The MOR model was applied and tested using the same real case study. The results from the three models were discussed and the differences are highlighted. A potential sensitivity analysis based on different levels of risk attitude was applied.

6.2 Dissertation Contribution

Despite the high volume of research on HCSC, the literature review has shown that the models that appeared in the literature are either for oil or gas supply chain and there is no paper that has covered oil and gas supply chain together. Moreover, from the literature, there are only two multi-objective optimization models developed for modeling HCSC (Iakovou (2001) and Azadeh et al. (2015). Iakovou (2001) formulated a multi-objective model for logistic of downstream oil supply chain under the assumption of fixed and known parameters.

Azadeh et al. (2015) developed a multi-objective fuzzy model for natural gas supply chain alone. The model considered the uncertainties in demand, capacity and cost of compressor and gas stations. Finally, incorporating the risk of uncertainty in the multi-objective stochastic model of HCSC has not appeared in the literature. Based on the shortcomes and gaps mentioned above, the dissertation contributions can be summarized as follows:

1. Developing three multi-objective optimization models for an integrated oil and gas supply chain simultaneously considering real constraints such as mass balance, demand, capacities, service level and OPEC quota.
2. Studying the tradeoffs between economic goals, keep sustain in market, and financial risk.
3. Integrating all downstream entities of HCSC in a single model including oil processing plants, refinery plants, gas plants, fractionation plants, bulk plants, and demand nodes (international, industries, and domestic).
4. Demonstrating how the model can assist in making tactical decisions regarding oil and gas processing, flow quantities, importation and exportation volumes, simultaneously.
5. Studying the impact of uncertainty in market conditions and mitigating and controlling the financial risk due to these uncertainties.

6.3 Future Research Directions

The research in this dissertation on HCSC can be extended and enhanced in several directions. The directions include, integration, modeling and optimization, and solution methodologies or approaches. In the direction of integration, still there are opportunities to integrate HCSC with other energy supply chains such as renewable energy (wind, solar or hydro systems). These type of systems may impact and enrich the existing optimization models.

From a modeling point of view, modeling and optimizing HCSC from a multi-objective and multi-dimension needs further research. In addition, it is important to take into consideration environmental aspects along with economic aspects during modeling of HCSC. The environmental aspects that can be studied along with economic purposes are the effect of emissions, security, and sustainability. Non-linearity is a key feature in HCSC problems that has received little attention.

The non-linearity in HCSC models arises from the formulation of oil reservoir performance equations, refining operations such as blending, and the risk measures. Another nonlinearity raise from transportation activity, where transportation cost has a nonlinear relation with transported quantity. A multi-stage stochastic programming can be used as a modeling approach because of its dynamic property, and it only has been utilized in a few of the reviewed papers. Also, robust programming approach could be used as a suitable tool to formulate problems under uncertainty.

Different transportation modes: in this work we considered all the transportation is done using pipelines, which is accurate for Saudi Arabia. For other HCSC different transportation modes may be used such as trucks, railways, and ships. Dependency between scenario based parameters and multi-stage stochastic formulation: in real life the values of prices and/or demand may not be independent. Price can take different values during the planning period (from period to another) and a dependency exist between these values based on market conditions. To investigate this case, we need historical information for the specified planning period from the stakeholders, so we can construct a dependent scenarios and applying a multi-stage stochastic formulation. Regarding solution approaches, adapting and/or developing quick and coherent efficient algorithms to solve large-scale models is a direction for future research. Meta-heuristic is an area less utilized in solving large scale HCSC problems and represents a promising area for future research.

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Appendix A: Collected Data

A.1 Petroleum Products

Crude oil types: Arabian extra light (AEL), Arabian light (AL), Arabian medium (AM), and Arabian heavy (AH).

Natural gas products: Associated gas (AS) and non-associated gas (NAS), Natural gas liquid (NGL), Methane (M), Ethane (E), Butane (B), Propane (P), Hydrogen sulfide (HS), and Natural gasoline (NG).

Oil products: LPG, Naphtha (NA), Gasoline (GA), Diesel (Di), Kerosene (Ke), Fuel oil (FO), and Asphalt (APH).

A.2 Oil and gas processing plants

Table A.1 Data about capacity of oil processing plants and refinery plants (1000 BL/day).

Oil processing plant	Oil type	Capacity	Refinery plant	Oil type	Capacity
Khurais	AL	1,500	Rastunura	AEL	550
Safaniya	AM, AH	1,500	Yanbu	AL	240
Qatif	AL, AM	1,500	Riyadh	AL	126
Khursaniyah	AL	1,500	Jiddah	AL	90
RasTanura	AH	1,500	PetroRabigh	AL	400
Shaybah	AL	1,500	SAMREF	AH	400
Tanajib	AL	1,500	SASREF	AH	400
Abqaiq	AEL, AL	70,000	SATORP	AH	400
			Jazan	AM	400

Table A.2 Data about capacity of processing and fractionation plants (Mscft/day).

Gas plant	Gas type	Capacity	Fractionation plant	Capacity
Uthmaniyah	AS	1500	Juaymah	2412.3
Berri	AS	600	Rastunura	1683
Shedgum	AS	1500	Yanbu	729.3
Khursaniyah	NAS	1000	Wasit	1346.4
Yanbu	NAS	520	Hawiyah	2805
Haradh	NAS	1600		
Hawiyah	NAS	2400		
Juaymah	NAS	2400		
Wasit	NAS	2500		

Table A.3 Yields of crude oil at oil processing plants

Oil processing plant	AXL	AL	AM	AH	Sulfur
Abqaiqs	0.9891				0.0109
Abqaiqs		0.9803			0.0197
Shaybahs	0.9891				0.0109
Khuraiss		0.9803			0.0197
Qatifs		0.9803			0.0197
Qatifs			0.9741		0.0259
Khuraniyahs		0.9803			0.0197
Safaniyas				0.9713	0.0287
Safaniyas			0.9741		0.0259
Tanajibs		0.9803			0.0197
Rastunuras				0.9713	0.0287

Table A.4 Yield of oil products at refinery plants

Oil processing plant	Refinery plant	LPG	NA	GA	KE	Di	FO	APH
Abqaiq	Rastunura	0.033	0.0799	0.234	0.05138	0.38	0.1834	0.03832
Abqaiq	Yanbu	0.0756	0.11	0.2354	0.0752	0.35	0.0538	0.1
Khurais	Riyadh	0.0948		0.2654	0.0752	0.395	0.0538	0.1158
Khuraniyah	Jiddah	0.1256	0.11	0.2354	0.0752	0.3	0.0538	0.1
Tanajib	PetroRabigh	0.1248		0.2654	0.0752	0.365	0.0538	0.1158
Rastunura	SAMREF	0.1248		0.0425	0.2101	0.2726	0.35	
Rastunura	SASREF	0.0255	0.2242	0.0425	0.1804	0.2726	0.2548	
Rastunura	SATORP	0.0255	0.2242	0.0425	0.1804	0.2726	0.2548	
Safaniya	Jazan	0.0561		0.1544	0.094	0.093	0.3575	0.245
Safaniya	Jazan	0.0561		0.1544	0.094	0.093	0.3575	0.245

Table A.5 Yields of gas products at gas plants

Gas plant	Natural gas type	NGL	M	HS
Uthmaniyaha	AS	0.352	0.62	0.028
Berria	AS	0.352	0.62	0.028
Shedguma	AS	0.352	0.62	0.028
Khursaniyaha	NAS	0.290	0.68	0.030
Yanbua	NAS	0.290	0.68	0.030
Haradha	NAS	0.290	0.68	0.030
Hawiyaha	NAS	0.290	0.68	0.030
Juaymaha	NAS	0.290	0.68	0.030
Wasita	NAS	0.290	0.68	0.030

Table A.6 Yield of gas products at fractionation plants

Gas plant	Fractionation plant	E	P	B	NG
Uthmaniyah	Rastunura	0.42	0.28	0.11	0.19
Berria	Juaymah	0.42	0.28	0.11	0.19
Shedguma	Yanbu	0.42	0.28	0.11	0.19
Khursaniyah	Juaymah	0.42	0.28	0.11	0.19
Yanbu	Yanbu	0.42	0.28	0.11	0.19
Haradh	Hawiyah	0.42	0.28	0.11	0.19
Hawiyah	Hawiyah	0.42	0.28	0.11	0.19
Juaymah	Juaymah	0.42	0.28	0.11	0.19
Wasit	Wasit	0.42	0.28	0.11	0.19

A.3 Distribution terminals

Table A.7 International demand of oil (1000 BL/day) and gas (Mscf/day).

Oil type	Demand	Oil products	Demand	Gas products	Demand
AEL	715	LPG	3.55	NGL	2333.76
AL	4004	NA	210	Hydrogen Sulfide	373
AM	1573	KE	137.061	Butane	105
AH	786.5	FO	58.89	Propane	250
				Natural Gasoline	251.72

Table A.8 Demands of distribution terminals (1000 BL/day)

	Demand node	LPG	GA	Ker	Di	FO	APH
Domestic regions	East	4.75	78.96	11.29	108.16	52.11	7.55
	West	10.6	176.12	25.19	241.24	116.23	16.85
	Middle	9.97	165.71	23.7	226.97	109.36	15.86
	North	1.78	29.57	4.23	40.51	19.52	0
	South	4.34	72.13	10.31	98.8	47.6	6.9
Industrial cities	Jubail	0	0	0	83	25.86	0
	Yanbu	0	0	0	83	25.86	0
	Rabigh	0	0	0	83	25.86	0

Appendix B: IMPROVED AUGMENTED ε-CONSTRAINED

AUGMECON method is a numerical technique used for generating the efficient Pareto-optimal solutions of the multi-objective optimization.

Problem definition

Assume a multi-objective optimization problem of p objective functions, x decision variables belong to S feasible space.

$$\max\left(f_1(x), f_1(x), \dots, f_p(x)\right) \tag{B.1}$$

st

$$x \in S$$

In the usual ε-constraint method the objective function with the highest priority is optimized subject to the other objective functions as constraints.

$$\max f_1(x) \tag{B.2}$$

st

$$f_2(x) \geq e_2,$$

$$f_3(x) \geq e_3,$$

$$\dots$$

$$f_p(x) \geq e_p,$$

$x \in S,$

where $e_1, e_2, \dots, and\ e_p$ are threshold values of the objective functions.

While the AUGMECON method optimizes the following model:

$$\max\left(f_1(x) + eps\ \left({s_2}/{r_2} + 10^{-1} \times {s_3}/{r_3} + \cdots + 10^{-(p-2)} \times {s_p}/{r_p}\right)\right) \tag{B.3}$$

st

$f_2(x) - s_2 = e_2,$

$f_3(x) - s_3 = e_3,$

...

$f_p(x) - s_p = e_p,$

$x \in S\ and\ s_i \in R^+$

Where $s_1, s_2, \dots, and\ s_p$ are the slack or surplus variables, $r_1, r_2, \dots, and\ r_p$ are the ranges of the objective functions, and $eps \in [10^{-6}, 10^{-3}]$.

Computational procedure for AUGMECON method

Step 1: Payoff table generation

The first step is to specify the range of each objective function applying a lexicographic optimization. Starting by optimizing the first objective function $f_1 = z_1^*$, then optimize the second objective function $(f_2 = z_2^*)$ adding $f_1 = z_1^*$ as a constraint. Thereafter, optimizing the third objective function $(f_3 = z_3^*)$ adding $f_1 = z_1^* and\ f_2 = z_2^*$ as a constraints and so on to finish all the objectives. Repeat the procedure starting from f_2 and continue until $f_{p.}$

Step 2: Efficient Pareto-optima generation

- Dividing the range of each objective function (i.e., equal intervals) to form a grid of possible Pareto points.
- Each point on the grid used as a right hand side of the (p-1) constrained objective functions. Then, solving the formulation (B.3), where the grid point that gives a feasible solution represents an efficient Pareto-optimal.

Vitae

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